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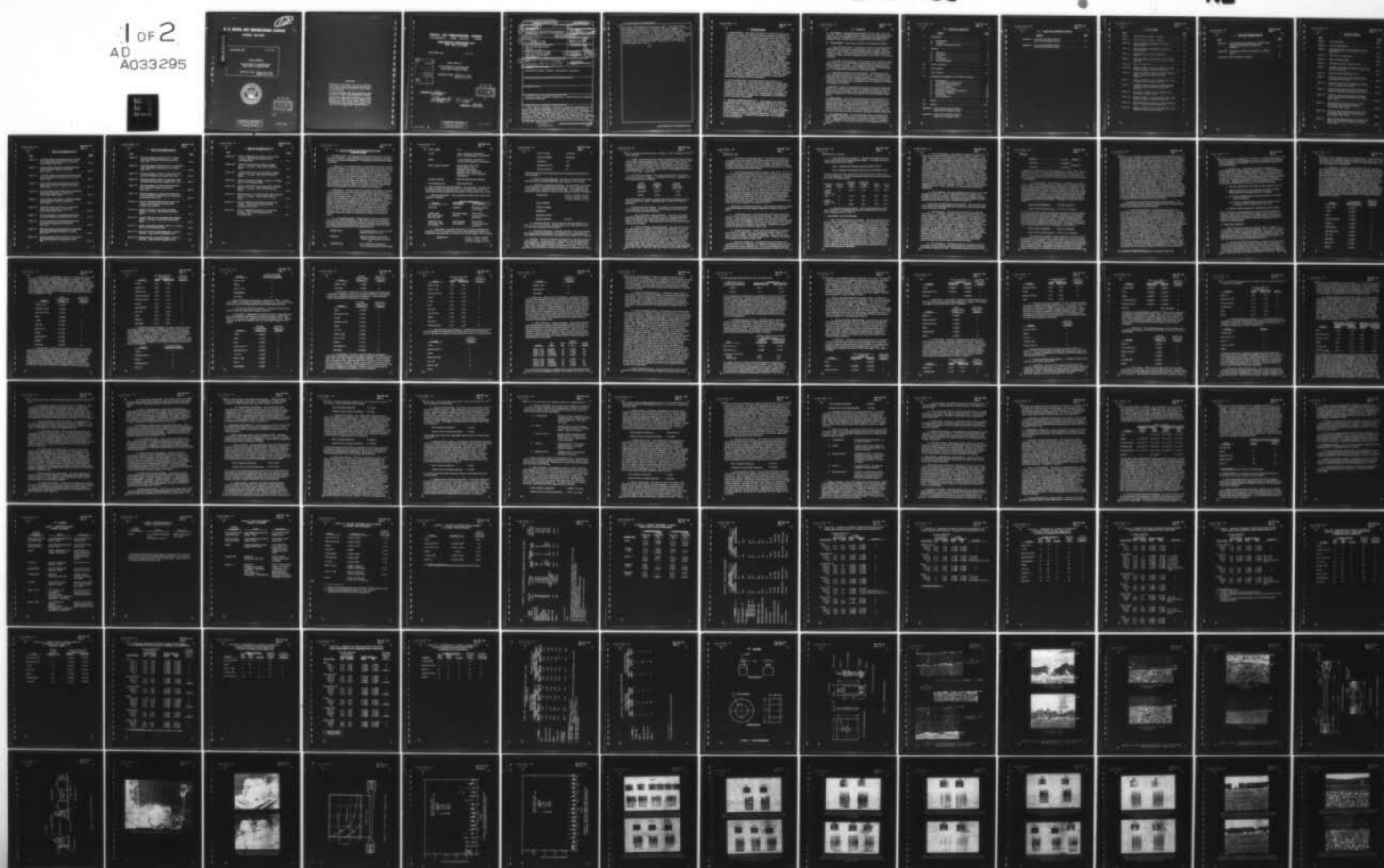

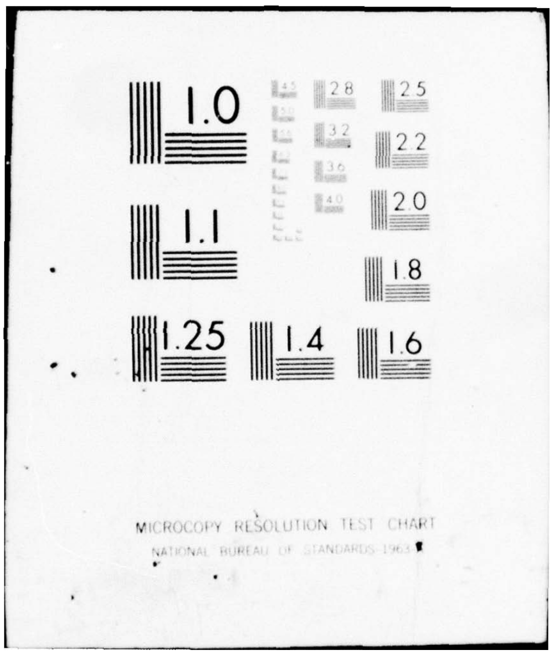
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LAKEHURST, NEW JERSEY

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NAEC-ENG-7884 23 Sep 1976

FINAL REPORT

EVALUATION OF COATINGS FOR AIR/FLUID ACCUMULATORS

CONTRACT NOS. N00156-74-C-1660
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FINAL REPORT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a sequential two-phase evaluation of the corrosion and wear resistance of ten coatings on AISI 4130 steel under conditions simulating those present in catapult accumulators and arresting gear accumulators used on aircraft carriers. In Phase I, ten coatings were subjected to wear tests and short-term corrosion tests. Five of these coatings were selected for additional evaluation in Phase II which included continued corrosion tests,

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wear tests and mechanical properties tests. The best overall performance was exhibited by Tribaloy 800 which appears to be the most promising coating for protection of both catapult and arresting gear accumulators. Other coatings which appeared satisfactory were, in order of decreasing effectiveness, Nedox and Selectron Ni-Co for use in the catapult accumulator and Selectron Ni-W and Nedox in the arresting gear accumulator. A Nylon 11 coating was unsatisfactory because of coating blistering in corrosion tests in both hydraulic fluids and in the simulated arresting gear wear tests.

I. INTRODUCTION

A. BACKGROUND. This report describes a two-phase program on the evaluation of coatings for wear and corrosion protection in cylinders of catapult accumulators and arresting gear accumulators used on Navy aircraft carriers. In both accumulator applications, wear and corrosion damage of the inner surfaces of the cylinders is experienced in service. Corrosion damage is particularly severe in the air space region and at the air-fluid interface where the piston is usually at rest. The degree of surface deterioration is such that it is frequently necessary to hone the cylinders and install oversize piston rings. The seriousness of the accumulator maintenance problem is the result of several factors. The location of the accumulators is such that it is extremely expensive to remove an accumulator, thus rework must be done in place. The limited working space around the accumulators also adds to the cost of rework. Although the accumulators may be reworked a number of times before requiring replacement, replacement is eventually necessary. Because of the large size of the accumulators and their locations in the ship, replacement is a major undertaking. Because of the severity of the accumulator maintenance problem, a solution was sought based on the application of wear and corrosion resistant coatings to the internal surfaces of the accumulator cylinders. In order for a coating system to be most beneficial, the coating must be applicable to existing on-board accumulators. For this reason, one of the criteria for coating selection was that the coating could be applied inside existing in-place accumulators.

B. EVALUATION PLAN. In the first phase of the program, ten coatings were subjected to wear tests and to short-term corrosion tests. On the basis of these test results, five of the coatings were selected for additional wear tests and for mechanical properties tests in the second phase of the program. Long-term corrosion tests continued into the second phase of the program. On the basis of the wear, corrosion, and mechanical properties test results plus metallographic examinations of selected test specimens, coatings were recommended for evaluation in actual accumulator applications.

C. PROGRAM PERFORMANCE DATA. This program was performed at Southwest Research Institute under contracts N00156-74-C-1660 and N68335-75-C-1118. The period of performance was from May 23, 1974 to September 30, 1975. The project leader at SwRI was R. D. Brown, Senior Research Engineer, Division of Fluids and Lubrication Technology, who was also responsible for the wear tests. H. C. Burghard, Senior Research Engineer, Division of Engineering Sciences was responsible for the corrosion tests, mechanical properties tests, and the metallographic examinations.

II. SUMMARY

A. MATERIALS. Materials included Bronze Alloy No. 865, Aluminum Alloy No. 355 T6, and AISI 4130 steel which are used in the actual accumulators; MIL-H-5559 Hydraulic Fluid, Arresting Gear and MIL-H-22072 Hydraulic Fluid, Catapult; and ten coatings on bare steel specimens.

B. PROCEDURES. Three types of tests were performed as follows:

1. Wear Test Procedures. Aluminum or bronze block specimens were loaded against rotating steel ring specimens, bare or coated. Contact pressures, sliding speeds, and fluid temperatures simulated those experienced in service. Wear test durations were 24-hr in Phase I and 72-hr in Phase II. Wear test data included ring wear, block wear, and coefficient of friction.

2. Corrosion Test Procedures. The corrosion tests consisted of alternate immersion of bare and coated test specimens in each of the two test fluids, maintained at 180°F. After exposure periods of approximately 1, 6, and 9 months, specimens were evaluated on the basis of visual appearance, low magnification examination, and weight change.

3. Mechanical Properties Test Procedures. Tapered tensile tests were conducted at maximum stress level of 70.0 ksi. Fatigue tests were conducted under tension-tension loading conditions at 35 cycles/sec and at a minimum stress of 20.3 ksi. Specimens were examined at low magnification and by liquid penetrant and magnetic particle techniques for evidence of cracking of the coating.

C. RESULTS. Using the combined wear test and corrosion test data from Phase I, five coatings were selected for additional evaluation in Phase II. On the basis of the corrosion, wear, and mechanical properties tests in Phase II coatings were ranked preferentially for each accumulator application.

D. CONCLUSIONS. The best overall performance was exhibited by Tribaloy 800 which appears to be the most promising coating for both accumulator applications. Other promising coatings, in order of decreasing effectiveness, Nedox and Selectron Ni-Co for the catapult accumulator and Selectron Ni-W and Nedox for the arresting gear accumulator. The failure of the Nylon 11 coating due to blistering of the coating in both the corrosion and wear tests was attributed to improper substrate preparation.

E. RECOMMENDATIONS. The Tribaloy 800 coating, and perhaps the Nedox coating, should be evaluated in full-size or small-scale accumulators. Additional corrosion and wear evaluation of Nylon 11 coatings are recommended, with particular attention to coating applications parameters.

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V. LIST OF FIGURES (CONT'D)

VI. EVALUATION OF COATINGS FOR AIR/FLUID ACCUMULATORS

A. *INTRODUCTION.* This program involved the evaluation of corrosion and wear resistant coatings that appeared promising to protect the inner surfaces of air/fluid accumulators. The program consisted of two sequential phases.

1. Objective. The overall objective of this program was the selection of coatings, platings, or surface treatments that will reduce the corrosion and wear prevalent in two types of shipboard air/fluid accumulators. The objective of Phase I was to provide wear data and short-term corrosion data on at least nine different surface coatings under conditions approximating those occurring in catapult accumulators and arresting gear accumulators on aircraft carriers. In Phase II of the program, the results of the first phase were augmented with additional corrosion data on the coatings evaluated in Phase I, additional wear data on five selected coatings, plus mechanical properties data on five selected coatings. Phase II also included metallographic evaluation of selected coating samples.

2. Background. The two air/fluid accumulator applications of interest to this program are involved in either the launching or arresting of aircraft on aircraft carriers. In one application, the catapult accumulator is a part of the catapult system used to launch aircraft. In the second application, the accumulator is a part of the aircraft arresting gear. Different fluids are used in the two applications, MIL-H-22072 Hydraulic Fluid, Catapult and MIL-H-5559 Hydraulic Fluid, Arresting Gear. In both applications, wear and corrosion of the inner surfaces of the accumulators have been experienced in service. Corrosion damage is particularly severe in the air space and at the air-fluid interface where the piston is usually at rest. The degree of surface deterioration is such that it is frequently necessary to hone the cylinders and install oversize piston rings.

a. Accumulator Details. Design details of the two accumulators are provided in NAEC Drawing Nos. H24-61404 Accumulator Assembly, Retraction Engine and 54-61933 Accumulator Assembly, Arresting Gear. As a basis for subsequent discussion, the nominal dimensions and typical operating parameters involved are summarised below:

Cylinder type:	Free floating piston, air on one side, hydraulic fluid on the other
Pressure:	3000 psi (Catapult accumulator) 750 psi (Arresting gear accumulator)
Cylinder bore:	18 in. (Catapult accumulator) 14 in. (Arresting gear accumulator)

Piston length:	12 in.
Travel:	38 in. (Catapult accumulator) 198 in. (Arresting gear accumulator)
Speed:	3-4 ips (Catapult accumulator) 66 ips (Arresting gear accumulator)
Piston contact material:	Bronze Alloy, QQ-C-390 Type I Alloy No. 865 (Catapult accumulator) Aluminum Alloy, QQ-A-601, Alloy No. 355 T6 (Arresting gear accumulator)
Cylinder material:	AISI 4130 (normalized condition)
Fluid temperatures:	180°F (maximum)

B. TEST MATERIALS AND SPECIMENS. Test materials, coatings, and test fluids used in the evaluation tests, and the details of the wear, corrosion and mechanical properties specimens are described in this section.

1. Specimen Materials. Three specimen materials were used in this program, as follows:

	Material Application in	
Material	Accumulator	Test Program
AISI 4130	Cylinders	Substrate material for coatings
Bronze alloy (QQ-C-390 Type I, Alloy No. 865)	Retraction engine bearing	Wear blocks Crevice corrosion specimens
Aluminum alloy (QQ-A-601, Alloy No. 355 T6)	Arresting gear piston spacer	Wear blocks Crevice corrosion specimens

a. Wear Rings. The AISI 4130 steel for the wear specimens was obtained as 1-3/4-in. diameter bar stock in the normalized condition; its composition and properties, as stated in the mill test report, are as follows:

Composition:	0.32 C, 0.53 Mn, 0.009 P, 0.009 S, 0.27 Si, 1.02 Cr, 0.21 Ni, 0.22 Mo, 0.13 Cu

Yield strength:	91,000 psi
Tensile strength:	96,500 psi
Elongation:	16%
Reduction of area:	53%
Brinell hardness:	207

Ring wear specimens were fabricated from this material without further heat treatment.

b. Steel Corrosion Specimens. The steel corrosion specimens were fabricated from normalized AISI 4130 sheet material, 1/8-in. thick.

c. Mechanical Properties Specimens. The material for the mechanical properties test specimens was purchased as 3/4-in. diameter and 5/8-in. diameter normalized AISI 4130 bar stock. The composition and properties of this material, as given by the mill test report are as follows:

Composition:	0.32 C, 0.52 Mn, 0.010 P, 0.011 S, 0.26 Si, 0.95 Cr, 0.14 Ni, 0.23 Mo, 0.29 Cu
Yield strength:	
Tensile strength:	
Elongation:	
Reduction of area:	
Brinell hardness:	207-212

d. Bronze Specimens. Bronze Alloy No. 865 was obtained in the form of 1-in. × 2-in. × 13-in. cast bars from which wear blocks and crevice corrosion specimens were machined.

e. Aluminum Specimens. Aluminum Alloy No. 355 T6 wear blocks and crevice corrosion specimens were machined from a used piston follower (NAEC P/N 613578-8) and a used piston spacer (NAEC P/N 613578-7).

2. Coatings. A total of ten different coatings were evaluated in Phase I of this program. The coating types, compositions, and the organizations which applied the coatings are given in Table I. All the coatings listed in Table 1 were subjected to both the corrosion and wear tests. Five of the coatings used in the Phase I testing were selected for additional wear tests

and for mechanical properties tests in Phase II, these coatings are identified in Table II.

3. Fluids. Corrosion and wear tests were performed in each of the two fluids used in shipboard applications: MIL-H-22072 Hydraulic Fluid, Catapult and MIL-H-5559 Hydraulic Fluid, Arresting Gear. The test fluid samples were obtained from hydraulic fluids removed from in-service accumulators at time of overhaul. The as-received viscosities were 44.7 cs (centistokes) and 9.2 cs, measured at 100°F, for the MIL-H-22072 and MIL-H-5559 fluids, respectively.

4. Wear Specimen Details. Wear specimen geometry and nominal dimensions are given in Figure 1. Hardness and surface roughness of the block specimens were as follows:

Block Specimen Material	Pretest Hardness R_B	Pretest Roughness, μin. CLA
Aluminum	50-58	12-24
Bronze	56-66	15-30

Coating thickness and surface roughness data for the ring specimens are given in Table III for Phase I specimens and in Table IV for Phase II specimens.

5. Corrosion Specimen Details. Two types of corrosion specimens were employed in the test program; a direct exposure specimen and a crevice corrosion specimen assembly.

a. Direct Corrosion Coated Specimens. The direct corrosion specimens consisted of 2-in. squares of 1/8-in. thick normalized AISI 4130 sheet material with a hole at the center for mounting in the test fixture, see Figure 2 (a). Each specimen of this type was coated on both sides and on the edges.

b. Crevice Corrosion Coated Specimens. The crevice corrosion test specimens were included to account for the possibility of a crevice existing between the piston and the cylinder wall. If such a situation exists, accelerated corrosion attack may occur within the crevice. The crevice corrosion assembly consists of a 1/8-in. × 1-in. × 2-in. coated AISI 4130 steel specimen clamped between two similar size specimens representative of the respective piston materials. Details for the crevice corrosion assembly are shown in Figure 2 (b). Aluminum alloy specimens (QQ-A-601, Alloy No. 355-T6) were employed for the crevice corrosion tests in MIL-H-5559 hydraulic fluid and bronze alloy specimens (QQ-C-390, Type I, Alloy No. 865) were used for tests in MIL-H-22072

hydraulic fluid.

c. Bare Steel Corrosion Specimens. Two sets of bare steel corrosion specimens were tested. One set was normalized in the laboratory by heating to 1650°F for two hours and air cooling. The second set was annealed by heating to 1650°F for two hours followed by furnace cooling. The heat treated bare steel specimens were surface ground prior to testing to remove the decarburised outer surface.

d. Coated Metallographic Control Coupons. One 1/8-in. × 2-in. × 2-in. control coupon was included with each set of corrosion test specimens coated by the various vendors to provide for metallographic characterization of the coating materials. These control coupons (except for the Hytrel coatings) were sectioned by conventional metallographic techniques to provide for direct measurement of the coating thickness and examination of the coating/substrate bond. Photomicrographs of these sections are shown in Figure 3. Microhardness measurements of the coating were also made on the metallographic sections. For the control coupons which were coated with Hytrel and Nylon 11 the coating thickness was measured by measuring the total specimen thickness and then measuring the substrate thickness after mechanically stripping a portion of the coating from the specimen. Coating hardness measurements were also made using a Rockwell Superficial Hardness Tester and coating surface roughness was measured using a Taylor-Hobson Talysurf. The coating characteristics determined from these control coupons are presented in Table V.

6. Mechanical Test Specimen Details. The mechanical properties tests performed in Phase II of the program employed two types of test specimens.

a. Tensile Specimens. Tapered uniaxial tensile specimens were used to evaluate the relative ductility of the coatings. These consisted of threaded, round uniaxial tensile specimens with a tapered test section. The test section was designed to provide for a stress level of approximately 40 percent of the yield strength at the large end when loaded to 110 percent of yield strength at the minimum cross section. Details of the tapered tensile test specimen are given in Figure 4 (a).

b. Fatigue Specimens. Fatigue tests were performed to evaluate the mechanical compatibility of the coating and substrate under the influence of cycle loading. Conventional threaded, round, 0.250-in. diameter tensile specimens were used for these tests. Details of the fatigue test specimens are shown in Figure 4 (b).

c. Specimen Preparation. The tapered tensile specimens were machined from 3/4-in. diameter bar stock and the fatigue specimens were fabricated from 5/8-in. diameter bar. Prior to machining the specimen blanks were normalised in the laboratory by heating to 1650°F for 1 hour

followed by air cooling.

d. Specimen Material Properties. Hardness measurements were made on each of the heat treated specimen blanks. The range of hardness values determined was as follows:

5/8-in. diameter bar (fatigue specimens) BHN 195-216

3/4-in. diameter bar (tapered tensile specimens) BHN 216-240

Uniaxial tensile tests were performed on two specimens of each bar size after heat treatment. The tensile properties determined for the normalized bar stock are tabulated below.

Specimen Type	Specimen No.	Ultimate Strength, ksi	0.2% Yield Strength, ksi	Elong., %	R. A., %
Tapered Tensile (3/4-in. dia. bar)	8	114.0	64.8	22.5	48.9
	14	111.8	58.8	24.5	44.3
Fatigue (5/8-in. dia. bar)	5	106.3	57.5	16.7	55.0
	7	108.6	60.0	16.0	58.9

e. Specimen Coating Thickness. The coating thickness for each type of specimen, as determined by diameter measurements before and after coating are listed in Table VI.

C. EQUIPMENT AND PROCEDURES

1. Wear Test Equipment and Procedures. The wear tests were run in the rig shown schematically in Figure 5. The actual test rig is shown in Figure 6. Two tests are run simultaneously in this rig, one at either end of the drive shaft. The essential rig components are shown on the left side of Figure 5. An upper (block) specimen is loaded against a rotating lower (ring) specimen. Normal load is applied by a weight directly above the line of contact. Friction force is measured by means of electric resistance strain gages bonded on the friction arm. The load arm carrying the block specimen is pivoted at a point on the line of action of the friction force, thus minimizing interactions between the normal and the friction forces. A timing motor and cam system is used to stop and reverse the motor to provide the desired reciprocating motion. Thermocouples are used to measure wear block temperatures and fluid temperatures and to activate the temperature controller.

a. Test Fluid System. Test fluids are contained in reservoirs (about 80 ml in Phase I tests and about 175 ml in Phase II tests). In all tests, a fluid level 1/16 inch above the bottom of the ring specimens was used. A cylindrical shield around the block specimen minimizes fluid loss due to splashing. Fluid makeup is provided by means of a feeder device connected to the reservoir. In Phase I tests, the feeder bottle and external reservoir (see Figure 6) were filled with the test fluid (MIL-H-5559 or MIL-H-22072). The same procedure was used in Phase II tests with MIL-H-5559 fluid, but in Phase II tests with MIL-H-22072 fluid, the feeder bottle and external reservoir were filled with distilled water. This latter procedure was effective in replacing water that evaporated from the MIL-H-22072 fluid during test, thereby maintaining fluid viscosity near that at which the fluid is used in service. In addition, fluid viscosity was checked once each 24 hours and either water or fluid was added to the test reservoir, as needed, to restore the proper viscosity. Viscosities generally ranged from 30.7 to 84.4 cs, except in tests 3, 4, and 6 in which maximum viscosities of 133.5, 338.7, and 692.1 cs resulted from an equipment malfunction.

b. Test Conditions. The test conditions used in each of the phases are given in Table VII. The test conditions for the two phases were identical except that the Phase I tests were of 24-hr. duration, whereas the Phase II tests were of 72-hr. duration and the MIL-H-22072 test fluid temperature was 180°F in Phase I and 160°F in Phase II.

2. Corrosion Test Equipment and Procedures. The corrosion tests were conducted by alternate immersion of bare and coated test specimens in each of the two test fluids.

a. Test Equipment. The tests were conducted in an apparatus consisting of a 7-1/2 gallon rectangular tank for the test fluid and a "ferris wheel" type specimen support fixture. A photograph of the apparatus is shown in Figure 7. Specimens are supported by a 3/8-inch diameter rod mounted between the two disks at each of six stations. The support fixture is mounted on bearings such that only the lower station is submerged in the test fluid, and fitted with a pneumatic indexing device to rotate the support fixture 60° at regular intervals. The apparatus includes heating elements, a temperature controller, and a lucite cover. All parts of the apparatus exposed to the test fluid are teflon coated or sheathed in tygon tubing. The specimens were separated by plastic spacers and electrically insulated from each other and from the support fixture. The indexing device was automatically actuated at 10-minute intervals providing for immersion of the specimens for 10 minutes followed by a 50-minute period of exposure to the air/vapor space above the liquid.

b. Test Procedures. Alternate immersion corrosion tests were conducted on sets of three of each specimen type to provide for evaluation after different exposure periods. The nominal exposure periods were as

follows:

Series I - - - - - - - - - - - - - - - - - - -	1 month	(Phase I)
Series II- - - - - - - - - - - - - - - - - - -	6 months	(Phase II)
Series III - - - - - - - - - - - - - - - - - -	9 months	(Phase II)

All tests were conducted with a fluid temperature at 180°F ±5°F. Prior to initiation of the tests each specimen (including the aluminum and bronze parts of the crevice corrosion assemblies) were solvent cleaned and accurately weighed (±0.0002 g) and their general appearance was documented by photographs.

(1) Fluid Control. During Phase I of the program, the fluid levels in the corrosion test apparatus were maintained by adding hydraulic fluid to make up for evaporation losses. This practice resulted in a continual increase in the viscosity of the MIL-H-22072 hydraulic fluid. The MIL-H-22072 fluid was drained and replaced after the initial three months of the corrosion test program, but no viscosity measurements were made during this period. During the fourth and fifth months the MIL-H-22072 fluid level was maintained by adding deionized water and the viscosity of both fluids was measured periodically. The range of viscosities was as follows:

MIL-H-22072 (Catapult): 283-658 centistokes

MIL-H-5559 (Arresting gear): 10.4-10.5 centistokes

At the end of the fifth month of the alternate immersion corrosion testing, both test fluids were drained and replaced. Subsequent to this operation the fluid levels were monitored on a daily basis and viscosity measurements were made at least twice weekly. The MIL-H-22072 fluid level was maintained by adding deionized water and the MIL-H-5559 fluid level was maintained by adding fresh hydraulic fluid. The range of viscosities over the remaining portion of the test program was as follows:

MIL-H-22072 (Catapult): 46 to 65 centistokes

MIL-H-5559 (Arresting gear): 10.6 to 11.2 centistokes

(2) Specimen Evaluation. Upon completion of each test series the specimens were removed from the test fixture, the crevice corrosion assemblies were dismantled. All corrosion test coupons for the particular series were rinsed in deionized water to remove residual fluid and deposits and accurately weighed. The coupons were then evaluated on the basis of visual appearance, low magnification (10-60X) examination and weight change. Any evidence of corrosive attack was documented photographically.

After the initial evaluation, selected specimens were chemically and/or electrolytically cleaned to remove all corrosion products and reweighed to provide weight loss data. Those specimens with metallic alloy or ceramic coatings were electrolytically cleaned in a water solution of a proprietary alkaline cleaning compound *. This technique is a commonly employed metallographic procedure and has been demonstrated to remove oxides and corrosion products from ferritic steels and certain other alloys without attack of the base metal. Prior to cleaning the corrosion test coupons, the metallographic control coupons were subjected to typical cleaning cycles as a test for attack of the particular coatings by the cleaning solution. No significant weight losses were noted in these tests. The aluminum alloy and bronze crevice corrosion coupons were chemically cleaned in accordance with ASTM G1 "Recommended Practice For Preparing, Cleaning and Evaluating Corrosion Test Specimens". A water solution sulfuric acid was used to clean the bronze coupons. The aluminum alloy coupons were cleaned in a water solution of chromic acid and orthophosphoric acid followed by dipping in concentrated nitric acid. Aluminum alloy and bronze blank, were subjected to the cleaning procedures prior to actual cleaning of the corrosion coupons as a test for chemical attack by the cleaning solutions. No significant weight losses were observed in these tests. Selected corrosion coupons were also sectioned and examined metallographically to establish the nature and extent of corrosive attack.

3. Mechanical Properties Test Equipment and Procedures. The mechanical properties tests consisted of tapered tensile tests and fatigue tests on both coated and uncoated specimens.

a. Tapered Tensile Tests. The tapered tensile tests were performed on an Instron Model TT universal testing machine. A stress level of 70.0 ksi at the minimum cross section was selected for the tests. This value was selected to represent approximately 110% of the maximum yield strength measured for the normalized bar stock (see Section VI B. 6). Prior to testing the coated specimens, a calibration test was performed on a bare tapered tensile specimen. Four electric resistance strain gages (1/16-in. gage length) were mounted at 0.2-in. intervals along the specimen starting at the point of minimum diameter. A uniaxial load sufficient to produce a stress of 70.0 ksi at the minimum cross section was applied (0.05 in./min crosshead speed) and the total strain indicated by each gage was measured. The specimen was then unloaded and the residual plastic strain at each gage point was recorded. The resulting strains are plotted versus position along the specimen in Figure 8. A maximum strain of 0.55 in./in. and residual plastic strain of 0.28 in./in. was recorded for the minimum cross section verifying that yielding occurred at this point. Duplicate specimens of each coating were tested at loads corresponding to 70.0 ksi (±0.5%) at the minimum section. After loading, each specimen was examined optically (10-50X) and by liquid penetrant

* Endox 214, Enthone Incorporated, West Haven Connecticut

and magnetic particle techniques for evidence of cracking of the coating. Selected specimens were sectioned on the axis and examined metallographically for evidence of cracking and to provide for additional measurements of coating thickness.

b. Fatigue Tests. The fatigue tests were performed on an Instron Model 1211 uniaxial fatigue testing machine. All tests were conducted under tension-tension loading conditions with a minimum stress of 1000 psi and at a frequency of 35 cycles/sec. Peak stress values of 20.3 ksi and 10.6 ksi were selected as representative of the maximum operating stresses for the catapult accumulator and arresting gear accumulator respectively. Duplicate specimens for each coating type were tested and the procedure established for this series of tests was as follows:

1. Test first specimen for 10^6 cycles at peak stress of 20.3 ksi.

2. Examine specimen for coating damage by optical (10-50X), liquid penetrant and magnetic particle techniques.

3. (a) Perform duplicate test on second specimen if no damage occurs in first test.

   (b) In event of coating damage in first test, perform test on second specimen at a peak stress of 10.6 ksi.

4. Examine second specimen for coating damage as in Step 2.

Prior to testing the coated specimens, two bare steel specimens were tested at a peak stress of 20.3 ksi (10^6 cycles) to assure that the test conditions did not result in damage to the base material. Selected specimens were sectioned on the axis and examined metallographically for evidence of coating damage.

D. WEAR TEST RESULTS

1. Phase I Simulated Catapult Accumulator Tests. In Phase I, a total of 24 wear tests were run using materials, fluid, and test conditions to simulate the catapult accumulator application. In general, two tests were run on each of 10 coatings and on the uncoated AISI 4130 steel. Two additional tests were run to provide data to confirm the performance of one of the more promising coatings (Selectron Ni-W).

a. *Friction and Wear Data Summary.* A summary of the friction and wear data from these tests is given in Table VIII. Friction data consists of the initial coefficient of friction and the average coefficient of friction for the period from 1-24 test hours. In all cases, the coefficient of friction was greatest at the start of testing and decreased rapidly with time, usually reaching a low steady value within the first hour. Wear data

consists of weight changes of block and ring specimens. Wear was generally slight in the simulated catapult accumulator tests; consequently, wear measurements based on the increase in size of the conforming area on the block specimens were not practical.

b. Ring Wear. The wear of the ring specimens was of primary concern since these specimens carried the various coatings under evaluation. Examination of the data in Table VIII shows that the wear of the ring specimens was almost negligible in most tests. The greatest ring weight loss occurred in Test 28 (Nylon 11 over wiresprayed aluminum); in this test, the nylon coating was completely removed from the wear track. In the tests involving metallic coatings, the greatest weight loss occurred in Test 37 (Nye-Kote) in which the weight loss of 0.0224 g corresponds to a loss of coating thickness of around 0.00013 in. Because of the small amount of ring wear in these tests, coupled with the apparent absorption of test fluid into the plastic materials and apparent deposits of transferred metal on the rings in other tests, it is difficult to assign a coating preferential rating on the basis of the ring wear data; however, it appears that the approximate order of coating preference for the catapult accumulator application is as follows:

Coating	Average Weight Change of Ring, g	Ring Wear Preferential Ranking
Nylon 11-B	+0.0160	1
T-800	+0.0152	2
None	+0.0067	-
Selectron Ni-Co	+0.0004	3
Nedox C	-0.0002	4
Diamondized	-0.0006	5
Selectron Ni-W	-0.0014	6
LW-11B	-0.0044	7
Nye-Kote	-0.0220	8
Nylon 11-A	-0.0633	9
Hytrel	-0.6345	10

c. Block Wear. A secondary criterion of coating performance is the wear of the block specimen rubbing against the coating. The block specimens in these tests represent the rubbing components of the piston in the catapult accumulator. Although the piston and its components are very much easier to replace than the accumulator cylinder, coatings which would cause rapid piston wear should be avoided in service applications. There were considerable differences in the amount of block wear caused by the various coatings, as shown by the average weight change data and preferential rankings given below:

Coating	Block Average Weight Change, g	Block Wear Preferential Ranking
Nylon 11-B	+0.0001	1
Selectron Ni-W	-0.0019	2
Selectron Ni-Co	-0.0020	3
None	-0.0042	-
T-800	-0.0060	4
LW-11B	-0.0079	5
Nylon 11-A	-0.0096	6
Hytrel	-0.0158	7
Diamondized	-0.0239	8
Nedox C	-0.3028	9
Nye-Kote	-4.0352	10

d. Friction Data. Friction was generally low under the simulated catapult accumulator conditions, especially after the initial drop in friction which occurred during the first hour of running. The average coefficient of friction at the start of the test is probably the most important friction data. In the accumulators, small shifts in piston position could cause sliding to occur on different surfaces and might result in prolonging the initial higher level of friction. Therefore the coating friction ratings assigned below are based primarily on initial coefficient of friction with equilibrium coefficient of friction as a secondary criterion where needed.

Coating	Average Coefficient of Friction Initial	Equilibrium	Friction Preferential Ranking
T-800	0.02	0.02	1
Nylon 11-A	0.04	0.01	2
Nylon 11-B	0.04	0.01	2
Selectron Ni-Co	0.04	0.02	3
Selectron Ni-W	0.07	0.02	4
Hytrel	0.07	0.04	5
Diamondized	0.08	0.02	6
LW-11B	0.12	0.03	7
None	0.14	0.02	-
Nedox C	0.14	0.03	8
Nye-Kote	0.16	0.06	9

e. Coating Performance Rankings. In order to select the better coatings for catapult accumulator applications in terms of friction and wear characteristics, the ring wear, block wear, and friction rankings were weighted 3, 2, and 1, respectively. The tabulation and summation of these weighted rankings are given in Table IX and the coatings are ranked in overall preferential order. These rankings, shown below, plus the rankings based on the catapult accumulator corrosion tests were used in recommending the coatings to receive further evaluation in the second phase of the program.

Coating	Friction and Wear Preferential Ranking
T-800	1
Selectron Ni-Co	2
Nedox	3
Selectron Ni-W	4
LW-11B	5

Coating	Friction and Wear Preferential Ranking
Nylon 11 (B)	6
Hytrel	7
Nylon 11 (A)	8
Diamondized	9
Nye-Kote	10

2. **Phase I Simulated Arresting Gear Accumulator Tests.** A total of 28 simulated arresting gear accumulator tests were run. At least two tests were run on each of 10 coatings and on the uncoated AISI 4130 rings.

a. **Friction and Wear Data Summary.** A summary of the friction and wear data from these tests is given in Table X.

b. **Ring Wear.** Examination of the data in Table X shows that ring wear was generally small except in the case of the plastic-coated rings (Nylon 11-A, Nylon 11-B, and Hytrel) and the diamondized rings. The preferential ranking of the coatings, based on ring weight changes, are as follows:

Coating	Average Weight Change of Ring, g	Ring Wear Preferential Ranking
T-800	+0.0042	1
Nedox	-0.0071	2
None	-0.0089	-
Selectron Ni-W	-0.0151	3
Selectron Ni-Co	-0.0304	4
LW-11B	-0.0320	5
Nylon 11 (B)	-0.3880	6
Hytrel	-0.4385	7
Diamondized	-0.4986	8

Coating	Average Weight Change of Ring, g	Ring Wear Preferential Ranking
Nylon 11 (A)	-2.9980	9
Nye-Kote	-6.8036	10

c. Block Wear. In the tests run under simulated arresting gear accumulator conditions, there were very large differences in the performance of the coatings as measured by block wear. The preferential coating rating based on block wear is as follows:

Coating	Average Weight Change of Block, g	Block Wear Preferential Ranking
None	-0.0102	-
Selectron Ni-Co	-0.0120	1
T-800	-0.0127	2
Selectron Ni-W	-0.0214	3
Nedox	-0.1120	4
LW-11B	-0.2310	5
Nylon 11 (B)	-0.5986	6
Nylon 11 (A)	-0.7230	7
Hytrel	-0.7311	8
Diamondized	-4.6399	9
Nye-Kote	-75.8928	10

d. Friction Data. Friction in the tests under arresting gear accumulator conditions was generally higher, especially the initial friction, than in the tests under catapult accumulator conditions. In the arresting gear accumulator tests, starting coefficients of friction of 0.20 or greater were observed for 6 coatings, whereas in the catapult accumulator tests, starting coefficients of friction did not exceed 0.16 in any of the tests. The preferential ranking of the coatings, as based on friction data from the simulated arresting gear accumulator tests is as follows:

Coating	Average Coefficient of Friction Initial	Average Coefficient of Friction Equilibrium	Friction Preferential Ranking
Nylon 11 (A)	0.03	0.01	1
Nylon 11 (B)	0.07	0.03	2
Selectron Ni-Co	0.16	0.02	3
Hytrel	0.18	0.06	4
T-800	0.19	0.02	5
None	0.20	0.02	-
LW-11B	0.26	0.03	6
Diamondized	0.26	0.08	7
Nedox	0.30	0.02	8
Nye-Kote	0.36	0.32	9
Selectron Ni-W	0.47	0.02	10

e. Coating Performance Rankings. The tabulated weighted rankings for the simulated arresting gear accumulator tests are given in Table XI and the coatings are ranked in overall preferential order, as repeated below:

Coating	Overall Preferential Ranking
T-800	1
Selectron Ni-Co	2
Nedox	3
Selectron Ni-W	4
LW-11B	5
Nylon 11 (B)	6
Hytrel	7

Coating	Overall Preferential Ranking
Nylon 11 (A)	8
Diamondized	9
Nye-Kote	10

3. Discussion of Phase I Wear Test Results. Although the friction and wear data presented in the two preceding sections permit a relative ranking of the coatings with regard to their friction and wear characteristics, there are several topics related to the test results which deserve discussion. In the remainder of this section, discussion will be devoted to the effect of Nylon-11 coating thickness on coating wear life, the probable causes of failure of the Hytrel coating, the effect of metal and carbide coating surface roughness on wear of the block materials, the observed increase in viscosity of MIL-H-22072A Hydraulic Fluid during the tests and the effect of increased viscosity on friction and wear results, and the relative severity of the simulated retraction engine tests and simulated arresting gear tests.

a. Effect of Nylon-11 Coating Thickness. Ring outside diameter measurements before coating, after subcoating, and after the Nylon 11 had been applied and turned for concentricity showed that there was considerable variation in the final Nylon 11 thickness. Because of this thickness variation it was felt that the Nylon 11 failures may have been related to coating thickness. However, coating thickness and ring wear data given below do not show any relation between coating thickness and coating failure in these tests.

Coating	Test Type	Test No.	Coating Thickness in.	Coating Failure
Nylon 11 (A)	Catapult	27	0.0035	No
Nylon 11 (A)	Catapult	28	0.0026	Yes
Nylon 11 (A)	Arresting	45	0.0046	No
Nylon 11 (A)	Arresting	46	0.0054	Yes
Nylon 11 (B)	Catapult	31	0.0032	No
Nylon 11 (B)	Catapult	32	0.0016	No
Nylon 11 (B)	Arresting	47	0.0032	No
Nylon 11 (B)	Arresting	48	0.0048	Yes

It is possible that the Nylon 11 coatings used in these tests failed because of one or more of the following reasons: all coatings were too thin, thus

permitting coating damage to initiate at irregular high spots in the sprayed metallic subcoatings; lack of concentricity of the metallic subcoats with the center of rotation could set up pulsations of the applied load; and absorption of hydraulic fluid may have softened the Nylon 11 or reduced the bond strength. In future tests, Nylon 11 coatings should be applied over subcoats that have a uniform thickness and thicker Nylon 11 coatings should be employed.

b. Hytrel Coating Performance. The Hytrel coatings appear to have little promise for either the catapult or arresting gear accumulator applications. Early coating failures occurred in all four tests run on this coating. Post-test examination of the ring specimens in both the simulated catapult accumulator tests and the simulated arresting gear accumulator tests revealed that the Hytrel coating had extruded from the wear track, indicating that the load-temperature combination was too severe.

c. Surface Roughness Effects. With regard to the coatings based primarily on metals or metallic carbides, there appeared to be a correlation between surface roughness or texture and wear of the block specimens, as shown in Table XII. Considering both types of tests, lowest block wear occurred in the tests involving the brush plated coatings (Selectron Ni-Co and Ni-W). These coatings were fairly smooth as evidenced by their mirror-like appearance and low surface roughness measurements (around 10μin. CLA). Although there was no significant difference in the surface roughness of the T-800 and the LW-11-B coatings, the latter coating caused the most block wear, especially in the case of the simulated arresting gear accumulator tests. This may be due to the greater hardness of LW-11B (tungsten carbide) as compared to T-800 (cobalt-nickel-chromium-silicon alloy). The diamondized coating had a lower measured surface roughness than did the Nedox coating, but in the simulated arresting gear accumulator tests the wear of blocks rubbing against the diamondized coating was more than 40 times that of the blocks rubbing against the Nedox. The greater wear in this case may be due to the presence of the numerous small diamond particles embedded in the electroless nickel matrix; these diamond particles may act as small cutting tools. The greater block wear may also be due to the surface texture of the electroless nickel matrix, especially since extremely high block wear was observed in all tests on Nye-Kote (electroless nickel). It should be noted that the Nye-Kote coatings did not have a mirror-like appearance but instead had a frosted appearance, suggesting a very fine microroughness of the surface which might act like a file. The Nedox coating is a porous nickel cutting and should have a fine surface microroughness, but the infused TFE may partially shield the microroughness and thus mitigate the cutting effect.

d. MIL-H-22072 Viscosity. It was noticed that the MIL-H-22072 Hydraulic Fluid used in the simulated catapult accumulator wear tests

thickened appreciably during the tests, as shown below:

Temperature at which viscosity was measured	Viscosity, cs	
	Before wear test	After wear test
100°F	44.7	765.1
210°F	9.1	94.2

This thickening was probably due to evaporation of water from the fluid during the 24-hr test. The MIL-H-22079 Hydraulic Fluid as used in service contains approximately 50% water and considerable evaporation of water would be expected at the 180°F fluid temperature used in these tests. Only a slight thickening of the MIL-H-5559 fluid was observed in the wear tests involving that fluid, which contains only about 3% water. The increase in viscosity of test fluids would, in general, decrease the severity of the tests by enhancing the formation of hydrodynamic lubrication films. In Phase II wear tests involving these fluids, the test fluid viscosity was controlled within ranges approximating those used in service maintenance.

e. Relative Severity of Tests. The examination of wear and friction data presented earlier in Tables VIII and X shows, that in general, ring wear, block wear, and friction were appreciably higher in the simulated arresting gear accumulator tests than in the simulated catapult accumulator tests. This difference in test severity is most easily shown by comparing the summation of ring wear, block wear, and friction data for the two types of tests, as follows:

Data	Average of Data for All Coatings for Indicated Tests	
	Catapult Accumulator	Arresting Gear Accumulator
Ring wear, g	-0.0626	-1.0196
Block wear, g	-0.4008	-7.5441
Coefficient of friction:		
Initial	0.08	0.22
Equilibrium	0.03	0.06

The greater severity of the simulated arresting gear accumulator tests is probably due to one or more of several causes. The total sliding distance in the simulated arresting gear tests is about 13 times that in the simulated retraction engine tests and corresponds roughly with the 16 times greater ring wear and the 18 times greater block wear experienced in the simulated arresting gear accumulator wear tests as

compared to the simulated catapult accumulator wear tests. The higher friction observed in the simulated arresting gear accumulator tests may be due to test fluid differences. The MIL-H-5559 Hydraulic Fluid, Arresting Gear is much less viscous than the MIL-H-22072 Hydraulic Fluid, Catapult and may not be as effective in developing a lubricating film. It is also possible that the MIL-H-22072 fluid contains better boundary lubrication additives. However, the very low friction after the first few minutes of testing observed in both types suggests that fluid film lubrication is acting to reduce friction.

4. Phase II Simulated Catapult Accumulator Tests. In Phase II, a total of 18 wear tests were run using materials, fluid, and test conditions to simulate the catapult accumulator application. Two 72-hr tests were run on each of the five coatings. Two additional tests, each of 1.5-hr duration were run on the Nedox coating. Extremely high block wear occurred in these two tests. The rings used in these tests were examined by the vendor and found to have improperly treated coatings. The coatings were reapplied and the rings were then used in complete 72-hr tests. A total of six tests were run on the uncoated AISI 4130 steel rings because of initial problems in controlling fluid viscosity.

a. Friction and Wear Data Summary. A summary of the Phase II friction and wear test data is given in Table XIII, Friction data consists of the initial coefficient of friction and the average coefficient of friction for the period from 1-72 hours. In nearly all cases, the coefficient of friction was greatest at the start of testing and decreased rapidly with time, usually reaching a low steady value within the first hour. Wear data consists of specimen weight changes, augmented, where possible, by wear track depth on the rings as measured with a Talysurf surface indicator.

b. Ring Wear. The wear of the ring specimens was of primary concern since these specimens carried the coatings under evaluation. In order to rank the wear resistance of the coatings, the average weight change data was converted to corresponding wear track depth. The ranking of the coatings on the basis of wear track depth on the rings is as follows:

Coating	Wear Track Depth, in., as Based on: Weight loss	Wear Track Depth, in., as Based on: Talysurf	Ring Wear Preferential Ranking
None	+	0.000070	-
Nedox	0.000020	0.000100	1
Selectron Ni-W	0.000051	0.000170	2

Coating	Wear Track Depth, in., as Based on Weight loss	Wear Track Depth, in., as Based on Talysurf	Ring Wear Preferential Ranking
T-800	0.000067	0.000020	3
Selectron Ni-Co	0.000148	0.000220	4
Nylon 11	+	0.000694	5

c. Block Wear. A secondary criterion of coating performance is the wear of the block specimen rubbing against the coating. The coatings are ranked on the basis of block wear, as follows:

Coating	Block Average Weight Change, g	Block Wear Preferential Ranking
Nylon 11	-0.0050	1
Selectron Ni-W	-0.0053	2
Selectron Ni-Co	-0.0054	3
None	-0.0149	-
Tribaloy 800	-0.0634	4
Nedox	-0.8918	5

d. Friction Data. Friction was generally low under the simulated catapult accumulator conditions, especially after the initial drop in friction which occurred during the first hour of running. The average coefficient of friction at the start of test was deemed the most important friction data, as discussed in the earlier section covering the Phase I wear test results. Therefore, the coating friction rankings assigned below are based primarily on initial coefficient of friction, with equilibrium coefficient of friction as a secondary criterion where needed. The variation of friction with time is shown in Figure 9.

Coating	Average Coefficient of Friction: Initial	Average Coefficient of Friction: Equilibrium	Friction Preferential Ranking
Nylon 11	0.06	0.01	1
Tribaloy 800	0.06	0.02	2

Coating	Average Coefficient of Friction Initial	Equilibrium	Friction Preferential Ranking
Selectron Ni-W	0.06	0.02	2
Nedox	0.09	0.01	3
Selectron Ni-Co	0.12	0.04	4
None	0.11	0.04	-

e. Coating Performance Rankings. In order to select the better coatings for catapult accumulator applications, the ring wear, block wear, and friction rankings were weighted 3, 2, and 1, respectively. The tabulation and summation of these weighted rankings are given in Table XIV and the coatings are ranked in overall preferential order. These rankings, given below, plus the rankings based on corrosion test and mechanical properties tests will be used later in recommending coatings for full-scale accumulator evaluations.

Coating	Overall Preferential Ranking
Selectron Ni-W	1
Nedox	2
Nylon 11	3
Tribaloy 800	4
Selectron Ni-Co	5

5. Phase II Simulated Arresting Gear Accumulator Tests. In Phase II, a total of 16 simulated arresting gear accumulator wear tests were run. At least two tests were run on each of the five coatings on the uncoated AISI 4130 rings.

a. Friction and Wear Data Summary. A summary of the friction and wear data is given in Table XV.

b. Ring Wear. The wear of the rings was measured by the weight loss method and also by the use of the Talysurf surface measuring instrument. Primary importance in rating ring wear was given to the weight loss method. The preferential ranking of the coatings based on ring wear, expressed as wear track depth, is as follows:

Coating	Wear Track Depth, in. as Based on Weight loss	Wear Track Depth, in. as Based on Talysurf	Ring Wear Preferential Ranking
Tribaloy 800	0.000079	0.000033	1
None	0.000098	0.000100	-
Nedox	0.000276	0.000195	2
Selectron Ni-Co	0.000308	0.000564	3
Selectron Ni-W	0.000313	0.000448	4
Nylon 11	+	Not measurable	5

The Nylon 11 coating exhibited a weight gain in these tests, suggesting it had absorbed some MIL-H-5559 fluid. Also, in both tests the coating failed either by blistering or cracking in the wear track. Because of these failures the Nylon 11 coating was ranked fifth on the basis of ring wear. The blistering of the Nylon 11 coating in these tests prevented accurate wear track depth measurement by means of the Talysurf instrument.

c. Block Wear. The preferential ranking of the coatings under simulated arresting gear accumulator conditions, as based on block wear, is as follows:

Coating	Average Weight Change of Block, g.	Block Wear Preferential Ranking
Nylon 11	-0.0014	1
Selectron Ni-Co	-0.0282	2
Selectron Ni-W	-0.0468	3
None	-0.0695	-
Tribaloy 800	-0.0825	4
Nedox	-0.1054	5

d. Friction Data. Initial friction coefficients in the simulated arresting gear accumulator tests were generally moderate, ranging from 0.06 to 0.27, and the equilibrium friction coefficients were very low, below 0.05 in all tests. The variation of friction with time is shown in Figure

10. The preferential ranking of the coatings, based on initial coefficient of friction, is as follows:

Coating	Average Coefficient of Friction Initial	Average Coefficient of Friction Equilibrium	Ranking
Nylon 11	0.06	0.01	1
Selectron Ni-W	0.10	0.01	2
Selectron Ni-Co	0.13	0.01	3
Tribaloy 800	0.16	0.02	4
None	0.19	0.04	-
Nedox	0.27	0.01	5

e. Coating Performance Rankings. The tabulated weighted rankings based on the Phase II simulated arresting gear accumulator wear tests are given in Table XVI. On the basis of the results of these tests the coatings are listed below in order of preference:

Coating	Ranking
Tribaloy 800	1
Selectron Ni-Co	2
Nylon 11	3
Selectron Ni-W	4
Nedox	5

It should be noted that, except for the bulging and coating separation observed after the 72-hr simulated catapult accumulator tests, the Nylon 11 coating exhibited little wear, caused the smallest amount of block wear, and had the lowest friction of any of the coatings. If the problem of coating penetration by the MIL-H-5559 fluid could be eliminated the Nylon 11 coating would appear to be a suitable coating for minimizing wear of both accumulator cylinders and pistons.

6. Discussion of Phase II Wear Tests. The friction and wear data presented in the two preceding sections permit a relative ranking, based on friction and wear considerations, of the five coatings evaluated in the Phase II wear tests. There are several topics related to coating perfor-

mance to the interpretation of the test results, and to use of the coatings in accumulator cylinders which deserve discussion. In the remainder of this section discussion will be devoted to the relative severity of the wear tests simulated retraction engine and arresting gear conditions, the comparison of Phase I and Phase II wear test results and the results of visual and metallographic examinations of the wear rings after tests.

a. Relative Severity of Phase II Wear Tests. By converting the wear data in Tables XIII and XV to wear rate expressed as wear volume/ring revolution it is possible to compare the relative severity of the simulated catapult accumulator wear tests and the simulated arresting gear accumulator wear tests. These wear rate data for the tests involving the uncoated rings and the metallic coated rings are given in Table XVII along with comparable data from Phase I tests on the same rings. Because of the different Nylon 11 coating thicknesses used in the Phase I and Phase II tests, the Nylon 11 wear data were not included in Table XVII. Considering only the Phase II data as shown below, it appears that the overall wear rates for both blocks and rings was greatest in the simulated catapult accumulator wear tests.

	Block Wear, $10^{-10} in^3/rev$		Ring Wear, $10^{-10} in^3/rev$	
	Simulated Accumulator		Simulated Accumulator	
Coating	Catapult	Arresting	Catapult	Arresting
None	5.02	5.35	0	0.41
Selectron Ni-W	1.78	3.59	2.82	1.28
Selectron Ni-Co	1.82	2.16	8.06	1.26
Nedox	300.	8.11	1.06	1.13
Tribaloy 800	21.4	6.34	3.66	0.32
Overall Average	66.0	5.11	3.12	0.88

In the Phase I tests, the overall wear rates of both blocks and rings were slightly greater in the simulated arresting gear accumulator tests. This change in relative severity may be attributable to two causes. First, the earlier tests involved a total of ten coatings, whereas the Phase II tests involved only five of the better coatings from the earlier work. Second, in the earlier tests the viscosity of the MIL-H-22072 fluid was not controlled and, due to the evaporation of water, very high viscosities (around 765 cs) were observed in those tests. In the Phase II tests, automatic water replacement techniques plus daily viscosity checks and adjustments resulted in maintaining viscosity generally in the range of 30.7 to 84.4 cs. The higher water content of the MIL-H-22072 test fluid and the lower fluid viscosity in the Phase II tests could contribute to either increased corrosion

or increased wear (due to decreased hydrodynamic lubrication effects) or both.

b. Comparison of Phase I and Phase II Wear Test Results. The wear data for uncoated steel and for the four metallic coatings used in both phases are summarized in Table XVII. The wear data has been expressed as wear volume per revolution in order to make valid comparisons between the 24-hr Phase I tests and the 72-hr Phase II tests. Comparison of the average wear rates for the four coatings shown indicates that, generally, there was little difference in wear rates in the two phases.

c. Visual Examination of Wear Specimens. The appearance of the wear rings and wear blocks, after test, are shown in Figures 11 - 22. In all of these figures, the wear blocks are lined up as closely as possible to the corresponding wear track on the appropriate ring.

(1) Uncoated Steel Rings. All of the uncoated rings and corresponding blocks for the wear tests run in both MIL-H-22072 and MIL-H-5559 fluids are shown in Figures 11 and 12. The smaller amount of wear experienced in the simulated catapult accumulator tests is evident since the worn areas on the blocks in Figure 11 are much less than those in Figure 12. It should be noted that the worn area on the block used in Test 8, shown in Figure 11, is almost exactly the size of the initial conforming section on the block.

(2) Selectron Ni-W Coated Rings. The wear of the bronze blocks which rubbed against the Selectron Ni-W coated rings was very slight in the simulated catapult accumulator tests, see Figure 13. Also, in these tests the ring wear tracks were highly polished in appearance and very shallow in depth. The aluminum blocks which rubbed against the Selectron Ni-W coated rings in the simulated arresting gear accumulator tests, (Figure 14) exhibited more wear than the bronze specimens shown in Figure 13. The wear tracks on the Selectron Ni-W rings subjected to the simulated arresting gear accumulator tests were also highly polished in appearance and slightly deeper than in the case of the simulated catapult accumulator tests.

(3) Selectron Ni-Co Coated Rings. The visual appearance of the Selectron Ni-Co coated rings and corresponding wear blocks shown in Figures 15 and 16, is very similar to that of the Selectron Ni-W coated rings described in the preceding paragraph.

(4) Nedox Coated Rings. In the tests involving Nedox coatings, block wear was greater in the simulated catapult accumulator tests, Figure 17, than in the simulated arresting gear accumulator tests, Figure 18. Roughening of the ring wear track was evident in the simulated arresting gear accumulator tests, Figure 18.

(5) Tribaloy 800 Coated Rings. The Tribaloy 800 coated rings exhibited highly polished wear surfaces in both types of tests, see Figures 19 and 20. Wear of the bronze blocks was less than that of the aluminum blocks.

(6) Nylon 11 Coated Rings. In the tests involving Nylon 11 coated rings, the wear of blocks in both types of tests was very slight, as shown in Figures 21 and 22. In the simulated catapult accumulator tests, Figure 21, very little wear and no deterioration of the Nylon 11 was evident. However, in the simulated arresting gear accumulator tests Figure 22, the Nylon 11 coating exhibited a break in one test and blistering in the other, although the coating exhibited very little wear.

d. Metallographic Examination of Ring Wear Specimens. After the wear tests, sections were cut from uncoated and coated ring specimens, nickel plated for edge protection, and mounted in plastic for metallographic grinding, polishing, and etching operations. The prepared sections were examined microscopically and photographed. Typical cross-sections of the wear rings are shown in Figures 23 - 32.

(1) Uncoated Steel Rings. In the case of the uncoated steel rings, Figures 23 and 24, a distinct layer approximately 0.001-in. thick was noted at the surface. This layer is very similar in appearance to the substrate material; it appears to be a wear deformed layer although small amounts of bronze or aluminum transferred from the block specimens may also be present.

(2) Selectron Ni-W Coated Rings. The Selectron Ni-W coated rings, Figures 25 and 26, exhibited a thin layer of material deposited over the Ni-W coating. This layer appears to be bronze or aluminum wear particles transferred from the wear blocks. It is significant that there is no evidence of coating debonding or other deterioration. As determined from the metallographic sections, the Selectron Ni-W coating thickness ranged from 0.001 to 0.002 in., which corresponds to the coating thickness of 0.0014 to 0.0022 in., determined from diameter measurements before and after coating, see Table IV.

(3) Selectron Ni-Co Coated Rings. A thin layer of transferred material was also evident on the wear surfaces of the Selectron Ni-Co coated rings, as shown in Figures 27 and 28. Coating integrity and bonding appear to be good. Coating thickness, as determined from the micrographs, ranged from 0.0015 to 0.004 in. which corresponds to the range of 0.002 to 0.0036 as determined by diameter measurements before and after coating, see Table IV.

(4) Nedox Coated Rings. In the case of the Nedox coated rings, Figures 29 and 30, the layer of transferred material was very much less than that observed on the Selectron Ni-W and Ni-Co coated rings. The

Nedox coating integrity and bonding appeared good. Coating thickness, from the micrographs, was 0.001 in, corresponding to 0.0011 in. based on diameter measurements before and after coating, see Table IV.

(5) Tribaloy 800 Coated Rings. The Tribaloy 800 coated rings exhibited a very irregular surface in the wear track and the coating appeared to be discontinuous and disrupted in several spots as shown in Figures 31 and 32. This is surprising since the wear tracks on the Tribaloy 800 coated rings appeared smooth and highly polished under visual observation. Coating thickness, from the micrographs, was around 0.005 in., corresponding to 0.0050 to 0.0057 in. based on diameter measurements before and after coating, see Table IV.

E. CORROSION TEST RESULTS. The data from all of the corrosion tests conducted in this program are tabulated in Appendices A, B, C, and D. The results of the tests on each group of coatings are summarized in the following sections.

1. Phase II Coatings in MIL-H-22072 Hydraulic Fluid. Corrosion test data for the bare 4130 steel specimens and the five Phase II coatings in MIL-H-22072 fluid are given in Appendix A. These data are summarized and discussed below for each type of coating.

a. Bare 4130 Steel. All steel specimens tested (two sets) suffered definite corrosive attack and the test data shows a consistent increase in severity of attack for the longer exposure times. The Series 3 tests (273 days) resulted in severe general corrosive attack accompanied by the formation of a heavy scale, see Figures A-1(a) and A-1(b). There was no significant difference in the extent of corrosion between the direct exposure specimens and the crevice corrosion specimens. The total weight loss for each of the Series 3 specimens (273 days exposure) was as follows:

Direct exposure specimens	1.44-1.76 gm
Coated crevice corrosion specimens	0.95-0.97 gm

The results of the alternate immersion tests on the bare steel specimens established that the MIL-H-22072 hydraulic fluid is an agressive environment for unprotected low-alloy steel. This test series also demonstrated that the corrosion test conditions employed in the program were severe enough to provide a reliable evaluation of the various coatings.

b. Nedox Coating. In general, the Nedox coating specimens survived the alternate immersion corrosion tests without significant corrosive attack. The surface layer of TFE separated and peeled off and a general darkening and slight roughening of the surface, indicative of mild general attack, occurred on both the direct exposure and crevice corrosion specimens, see Figure A-1(c). Definite susceptibility to crevice corrosion was indicated by pitting attack at the bottom of the Series

3 crevice corrosion specimen, Figure A-2. The weight loss for each of the Series 3 coated specimens was as follows:

Direct exposure specimen	0.077 gm
Coated crevice corrosion specimen	0.04 gm

c. Tribaloy 800 Coating. The Tribaloy 800 coating exhibited a general resistance to corrosive attack. The surface condition of all specimens after tests indicated that little or no general corrosion occurred, see Figure A-1(d) and Figure A-3. Some loss of plating by flaking occurred at the edges of the Series 3 test specimens. This effect may be due to ineffective application of the coating at the edges. Separation and flaking of the coating occurred at one small spot on the Series 3 direct exposure coupon. This flaking appeared to result from an initial plating defect. The localized loss of plating on these specimens is not considered as indicative of general susceptibility to corrosive attack. The weight loss measured for each Series 3 coated specimen was as follows:

Direct exposure specimen	0.1428 gm
Coated crevice corrosion specimen	0.1585 gm

It should be noted that the weight loss includes localized loss of plating at the specimen edges and that no significant attack of the coating was observed in the metallographic examination. No evidence of crevice corrosion was observed in any of the Tribaloy 800 specimens.

d. Nylon 11(A) Coating. The Series 1 and Series 2 tests on the Nylon 11(A) specimens did not result in any observable damage to the coating. In the Series 3 tests several small blisters developed in the coating, see Figure A-4. The remainder of the coating appeared undamaged. The blisters were cut open and peeled back and it was observed that the blister contained test fluid and that some corrosion of the underlying substrate had occurred. The Nylon 11(B) specimens (Phase I specimens for which corrosion tests only were continued in Phase II) exhibited a similar behavior in the tests and photographs of the Series 3 test specimens are included in Figure A-4. It should be noted that metallographic examination of the control specimens revealed an irregular subcoating layer and some evidence of localized poor bonding was observed, see Figures 3(d) and 3(e). Also NAEC personnel reported priming techniques employed were not optimum, this is discussed more fully in Section VI-G. These factors suggest that the blistering may be associated with substrate preparation and coating application techniques and may not be an inherent characteristic of the coating itself. All of the Nylon 11 specimens exhibited a weight gain generally consistent with exposure time. The weight gain in the Series 1 and Series 2 tests may be indicative of absorption of fluid by the coating. However, it must be recognized that

at least part of the weight gain in the Series 3 tests is associated with the fluid contained within the blister.

e. Selectron Ni-W Coating. The Selectron Ni-W specimen suffered corrosive attack in all tests. Some pitting of the coating was noted in the Series 1 tests and evidence of general corrosive attack was apparent in the Series 2 tests. The Series 3 tests resulted in severe corrosion and heavy scale build-up as shown in Figure A-1(f). After cleaning of the Series 3 specimens, nearly complete loss of the coating was visually apparent, (Figure A-5a) and subsequently verified in the metallographic examination, see Figure A-5(b). The weight loss measured for the Series 3 specimens was as follows:

Direct exposure specimen	1.51 gm
Coated crevice corrosion specimen	0.61 gm

These weight loss values are comparable to those noted for the bare steel specimens.

f. Selectron Ni-Co Coating. The results of the alternate immersion tests on the Selectron Ni-Co specimens indicated a relatively high resistance to general corrosive attack (Figure A-1g). The surface condition after cleaning and the metallographic examination indicated little or no direct corrosive attack of the coating, Figures A-6(a) and A-6(b). Corrosive attack did occur at the edges of the specimens but this effect may be associated with difficulties in plating of the specimen edges. Susceptibility to crevice corrosion was indicated by pitting at the bottom of the crevice corrosion specimen and under the spacers on the Series 3 specimens, see Figures A-6(a) and A-6(c). The weight loss incurred by each of the Series 3 specimens was as follows:

Direct exposure specimen	0.33 gm
Coated crevice corrosion specimen	0.36 gm

It should be noted that these weight loss values included edge attack and crevice pitting.

g. Bronze Crevice Corrosion Specimens. In all tests conducted in the MIL-H-22072 hydraulic fluid, the bronze crevice corrosion coupons suffered mild corrosive attack. All bronze coupons exhibited a weight loss and the weight losses measured were consistent with exposure time. The average weight loss for the pairs of bronze coupons employed in the Series 3 tests (237 days to 273 days exposure) was very consistent among the various types of specimens and ranged from 0.152 to 0.212 gm. These results indicate that the coatings tested do not result in accelerated

attack of the bronze alloy due to galvanic action in a coupled specimen.

h. Rating of Coatings. On the basis of the results of the alternate immersion corrosion tests the five coatings tested in Phase II of the program may be rated in order of preference and suitability for service in MIL-H-22072 hydraulic fluid as follows:

1.	Tribaloy 800	Surface condition indicates little or no general attack. Weight loss attributed to edge attack. No crevice corrosion.
2.	Nedox	Surface condition and low weight loss indicates resistance to general attack. Crevice corrosion.
3.	Selectron Ni-Co	Surface condition indicates mild general attack. Weight loss includes edge attack. More severe crevice corrosion.
4.	Nylon 11	Coating blistered. (No apparent coating damage or corrosion except at blisters.
5.	Selectron Ni-W	Complete failure of coating and corrosion of substrate.

2. Phase II Coatings in MIL-H-5559 Hydraulic Fluid. Corrosion test data for the five Phase II coatings and the bare 4130 steel in MIL-H-5559 fluid are given in Appendix B. These data are summarized and discussed below for each type of coating.

a. Bare 4130 Steel. No significant corrosion of any of the bare steel samples (two sets) occurred in the alternate immersion tests in the MIL-H-5559 hydraulic fluid. A thin blue film developed on all specimens but there was no evidence of any rusting or pitting on any specimen. See Figure B-1(b). There was no significant differences in appearance or weight loss among the various test coupons (34 to 281 days exposure). Also no evidence of crevice corrosion was observed in any of the aluminum-steel test specimen assemblies. The total weight loss for each of the Series 3 specimens (281 days exposure) was as follows:

Direct exposure specimens	0.0004 - 0.013 gm
Coated crevice corrosion specimens	0.003 - 0.017 gm

The results of the alternate immersion tests on the bare steel specimens showed that the MIL-H-5559 hydraulic fluid is not corrosive to unprotected low-alloy steel.

b. Nedox Coating. The Nedox coating specimens survived the alternate immersion corrosion tests without evidence of major corrosive attack. The surface layer of TFE peeled off in all tests. Some roughening of the surface was observed and was more pronounced in the Series 3 specimens (261 days exposure), see Figure B-1(c). The metallographic examination of the Series 3 direct exposure coupon established that the coating was intact but the outer surface appeared slightly irregular, Figure B-2. These factors indicate mild corrosive attack of the coating. No evidence of susceptibility to crevice corrosion was noted. The total weight loss for the Series 3 specimens was as follows:

Direct exposure specimen	Undetermined
Coated crevice corrosion specimen	0.019 gm

c. Tribaloy 800 Coating. The Tribaloy 800 coating specimens exhibited a high resistance to corrosion in the MIL-H-5559 hydraulic fluid. There was no visual evidence of general attack or crevice corrosion on any of the test specimens (Figure B-1(d) and the measured weight losses were the lowest of any coating tested in this fluid. A plating defect was present in the Series 2 direct exposure coupon. The plating was intact but separated from the substrate and slightly bulged at one location. No evidence of corrosion was observed at this location. Apparently this defect was associated with inadequate substrate preparation procedures. An intergranular network was observed on the coating surface after testing, see Figure B-3(a). Similar features were observed on the Tribaloy 800 specimens tested in MIL-H-22072 fluid. Metallographic examination of the direct exposure specimen established that this network was a surface effect, see Figure B-3(b). Also no evidence of any corrosive attack was observed in the metallographic section. The total weight loss for the Series 3 specimens (267 days exposure) was as follows:

Direct exposure specimen	0.0 gms
Coated crevice corrosion specimen	0.023 gm

d. Nylon 11(A) Coating. The Series 1 tests on the Nylon 11(A) specimens did not result in any observable damage to the coating. The Series 2 direct exposure specimen survived 189 days exposure without damage but the crevice corrosion specimen developed a major blister in the coating. In the Series 3 tests major blister developed on both sides of the direct exposure and the crevice corrosion coupons, see Figure B-1(e) and Figure B-4(a). Several of the blisters were cut open and peeled back and in each case the blisters contained test fluid. The sub-

strate surface at the blisters was clean and bright and there was no visual evidence of corrosion. The Nylon 11(B) specimens (Phase I specimens for which corrosion tests were continued in Phase II) also developed severe blistering in the Series 2 and Series 3 tests and photographs of the Series 3 specimens are shown in Figure B-4(b). It should be noted that all Nylon 11 test specimens exhibited a similar behavior in the MIL-H-22072 and the MIL-H-5559 hydraulic fluids. Also, in all tests, no evidence of damage to the coating material itself was noted. As discussed in Section VI-C, 1d, the blistering may be associated with substrate preparation and coating application procedures and does not necessarily indicate that the coating is unsatisfactory for service in these two hydraulic fluids. All of the Nylon 11 specimens tested in the MIL-H-5559 hydraulic fluid showed a weight gain. The weight gain in the Series 1 tests is indicative of absorption of fluid by the coating but the weight gain measured in the longer exposure tests includes the fluid contained within the blister. This trapped fluid probably accounts for the major portion of the weight change measured for those specimens which blistered.

e. Selectron Ni-W Coating. The results of the alternate immersion tests on the Selectron Ni-W specimens indicated mild general corrosive attack of the coating. A tight dark film developed on the Series 1 specimens (22 days exposure) and patches of roughened surface were present on the Series 3 specimens (253 days exposure), see Figure B-1 (f). The metallographic examination of the Series 3 direct exposure coupon revealed a rough outer surface and possible penetration of the coating verifying corrosive attack, see Figure B-5. Minor pitting was observed at the bottom of the Series 2 and Series 3 crevice corrosion coupons indicating a possible susceptibility to crevice corrosion attack. The total weight loss for the Series 3 specimens was as follows:

Direct exposure specimen	0.087 gm
Coated crevice corrosion specimen	0.049 gm

f. Selectron Ni-Co Coating. The alternate immersion corrosion tests in MIL-H-5559 fluid resulted in severe corrosive attack of the Ni-Co Coating. There was no indication of significant attack in the Series 1 tests but the surface condition of the Series 2 specimens indicated mild attack of the coating. The Series 3 direct exposure and crevice corrosion coupons exhibited a mottled appearance with evidence of coating loss after 253 days exposure, see Figure B-1(g). After cleaning, complete loss of the coating over the major portion of the surfaces of both specimens was evident as shown in Figure B-6(a). Metallographic examination of the direct exposure coupon verified the coating loss, see Figure B-6(b). The total weight loss for the Series 3 specimens (253 days exposure) was as follows:

Direct exposure specimen	0.400 gm
Coated crevice corrosion specimen	0.120 gm

g. Aluminum Alloy Crevice Corrosion Specimens. In all tests conducted in the MIL-H-5559 test fluid no significant corrosion of the aluminum alloy crevice corrosion coupons occurred. No measurable weight loss occurred in three of the six cases and weight loss in the other three cases was 0.002 gm and 0.003 gm (see Appendix B, pages B-2 to B-8). These results indicate the coatings tested do not result in accelerated corrosion of the aluminum alloy due to galvanic action in a coupled specimen.

h. Rating of Coatings. On the basis of the results of the alternate immersion tests, the five coatings tested in Phase II of the program may be rated in order of preference and suitability for service in MIL-H-5559 hydraulic fluid as follows:

1.	Tribaloy 800	No significant general attack. No crevice corrosion.
2.	Nedox	Surface condition and weight loss indicates slight general attack. No crevice corrosion.
3.	Selectron Ni-W	Mild general attack. Indication of significant thinning or penetration of coating in 253 days exposure. Possible susceptibility to crevice corrosion.
4.	Nylon 11	Coating blistered. (No apparent damage to coating material).
5.	Selectron Ni-Co	Failure of coating due to general corrosive attack resulting in complete loss of coating over major portion of specimen surfaces.

3. Phase I Coatings. Five of the original ten coatings tested in Phase I of the program were deleted from the Phase II wear test program based on the Phase I wear test results and the Series 1 corrosion test results (approximately one month exposure). The alternate immersion corrosion tests on these coatings were continued in Phase II. The data from these tests and photographs of the Series 3 test specimens are included in Appendices C and D. In general, each of these coatings failed the corrosion test in one or both of the two hydraulic fluids. The results of the tests on each coating are summarized below.

a. Hytrel Coating. The Series 2 and Series 3 Hytrel specimens failed completely in both fluids after 95 days exposure, see Figures C-1 (a) and D-1(a).

b. LW-11B Coating. Severe corrosive attack and loss of coating occurred in both fluids, see Figures C-1(b) and D-1(b). The coating loss (and attack of substrate in the MIL-H-22072 fluid) was accompanied by major weight loss.

c. Nylon 11(B). The Series 1 and Series 2 Nylon 11(B) specimens developed major blisters in both test fluids, see Figures C-1(c) and D-1 (c). (Also see Figures A-4 and B-4 and discussion of the Phase II Nylon 11(A) best results).

d. Diamondized Coating. The diamondized coating suffered severe corrosive attack in both test fluids. The tests in the MIL-H-22072 fluid resulted in severe pitting of the coating and corrosive attack of the substrate, Figure C-1(d) and severe general attack of the coating occurred in the MIL-H-5559 fluid.

e. Nye-Kote Coating. Essentially complete loss of the coating occurred on the Series 2 and Series 3 specimens tested in the MIL-H-5559 fluid after 95 days exposure, see Figure D-1(e). The tests on all Nye-Kote specimens (both fluids) were terminated at this time. Some general attack of the coating occurred in the MIL-H-22072 fluid (Figure C-1e) but this attack was not as severe as that in the MIL-H-5559 fluid.

F. MECHANICAL PROPERTIES TEST RESULTS. The mechanical properties tests consisted of tapered tensile tests and fatigue tests on both coated and uncoated specimens.

1. Tapered Tensile Test Results. Duplicate tests were run on each coating at a stress level of 70.0 ksi at the minimum cross section. This stress corresponds to approximately 110% of the maximum yield strength measured for the normalized bar stock. After loading, each specimen was examined optically (10-50X) and by liquid penetrant and magnetic particle techniques for evidence of cracking of the coating. No cracking was observed on any of the coatings. One specimen of each coating type, except the Nylon 11 specimens, was sectioned along the axis and examined metallographically for evidence of coating cracking or other coating failure. No cracking or other evidence of coating failure was observed on any of the specimens.

2. Fatigue Test Results. Duplicate fatigue tests were performed on each coating type. All tests were conducted under tension-tension loading conditions with a minimum stress of 1.0 ksi, a peak stress value of 20.3 ksi, at a frequency of 35 cycles/sec, and at a test duration of 10^6 cycles. All specimens were examined optically (10-50X) and by liquid

penetrant and magnetic particle techniques for evidence of cracking. No cracking was observed on any of the coatings. One specimen of each coating type, except the Nylon 11 coated specimens, was sectioned along the axis and examined metallographically. No evidence of cracking or other coating deterioration was observed on any of the specimens.

3. Significance of Mechanical Properties Test Results. The fact that no evidence of coating failure or deterioration was observed on any of the mechanical properties test specimens indicates that all of the coatings are compatible with the AISI 4130 steel base material for the stress levels employed in these tests.

G. DISCUSSION OF RESULTS. Topics of discussion include an anomaly in the Tribaloy 800 results factors affecting Nylon 11 performance, the practical significance of the wear test results, and the overall ranking of the coatings.

1. Anomaly in Tribaloy 800 Results. The Tribaloy 800 coating exhibited the best overall corrosion and wear protection in both of the test fluids. One anomaly in the results requires discussion however. Metallographic examination of the wear track sections of specimens after wear tests in each of the test fluids revealed a very irregular surface in the wear track and discontinuties in the Tribaloy 800 coating, see Figures 31 and 32. This is surprising since the wear tracks on the Tribaloy 800 coated rings appeared smooth and highly polished, and weight loss data indicated very little wear of the Tribaloy 800 coated rings. It is believed that the Tribaloy 800 coatings were damaged in the metallographic sectioning prior to nickel plating. Evidence of such damage, or of a coating application defect was also apparent in metallographic examination of the corrosion specimens, see pages A-3 and B-3.

2. Nylon 11 Performance. The Nylon 11 coating failed due to blistering in corrosion tests in both fluids and blistering and coating splitting in wear tests in the MIL-H-5559 fluid. These failures are not necessarily inherent to the Nylon 11 coating, but may be due to improper substrate preparation and priming procedures. Metallographic examination of the Nylon 11 control specimens revealed an irregular subcoating layer and some evidence of localised poor bonding, as shown in Figures 3(d) and 3(e). Also, NAEC personnel reported that the primer used on the corrosion specimens and the Phase I wear specimens, Rislan Primer P, is not the optimum primer base for Nylon 11. In addition, the wiresprayed aluminum subcoating on the Phase II wear specimens was sealed with a sealant (Metcoseal) by the wirespray vendor. Better bonding of the Nylon 11 to the subcoating would have been achieved without the sealant.

3. Practical Significance of Wear Results. The wear and friction results presented earlier showed differences in performance among the

five coatings evaluated. However, from a practical view, the friction and wear properties of all of the coatings are either comparable to or better than those of the bare steel. The wear rates of the coatings and of the bronze and aluminum coatings sliding against the coatings are very low. The average wear for each coating and corresponding counterface material were converted to wear rate expressed as in/cycle, where each cycle consists of the piston moving down and back as in typical operation. These wear rates are given below:

	Wear, in. /cycle			
	Catapult Accumulator		Arresting Gear Accumulator	
Coating	Coating Wear	Block Wear	Coating Wear	Block Wear
None	—	1.4×10^{-7}	0.7×10^{-10}	5.8×10^{-7}
Nedox	1.8×10^{-10}	8.3×10^{-6}	1.9×10^{-10}	8.7×10^{-7}
Selectron Ni-W	4.8×10^{-10}	5.0×10^{-8}	2.2×10^{-10}	3.9×10^{-7}
Tribaloy 800	6.2×10^{-10}	5.9×10^{-7}	0.5×10^{-10}	6.8×10^{-7}
Selectron Ni-Co	13.7×10^{-10}	5.0×10^{-8}	2.2×10^{-10}	2.3×10^{-7}
Nylon 11	—	4.7×10^{-8}	—	0.4×10^{-7}

On the basis of the calculated wear rates given above the number of cycles required to produce 0.001 in. wear of the least wear resistant coating for each application is 730,000 for the catapult accumulator and 4,545,000 for the arresting gear accumulator. The wear per cycle on the block material is considerably higher since the block material is in continuous sliding contact throughout the cycle. However, only one coating, Nedox in the simulated catapult accumulator wear tests, caused a block wear rate significantly greater than that of uncoated steel. The wear rate of the bronze wear blocks sliding on Nedox was about 60 times that when sliding on uncoated steel. Even this wear rate may not be excessive in practice, since much of the normal load on the piston may be borne by the packing, and also, the pistons and piston rings are relatively easy to replace in contrast to the accumulator cylinders or the cylinder coatings. The low wear rates observed in the wear tests suggests that corrosion is the major cause of surface deterioration in the accumulators in service, or that, once corrosion damage occurs, it serves to roughen the sliding surfaces causing much higher wear rates than observed in these tests.

4. **Overall Coating Performance Rankings.** In order to rank the overall performances of the coatings on the basis of both wear and corrosion test results, the earlier wear and corrosion rankings have been summarized in Table XVIII. As mentioned in the preceding paragraph, the

friction and wear properties of all five coatings are satisfactory; consequently, corrosion resistance is the primary criterion in ranking the coatings. Corrosion tests results indicate that Tribaloy 800 and Nedox provided substantially greater corrosion resistance in both test fluids than did the other coatings. Tribaloy 800 appears to be the coating most likely to provide satisfactory protection in both accumulator applications. The Nedox coating exhibited low, general corrosive attack but it suffered some crevice corrosion attack in MIL-H-22072 fluid. Selectron Ni-Co suffered mild general attack in MIL-H-22072 fluid, but it suffered some crevice corrosion attack. In the MIL-H-5559 fluid, the Selectron Ni-Co suffered complete loss of coating. The Selectron Ni-W coating did not fail in MIL-H-5559 fluid but it suffered more general attack than either the Tribaloy 800 or the Nedox coatings. In MIL-H-22072 fluid, the Selectron Ni-W suffered complete loss of coating. As mentioned earlier the Nylon 11 coating suffered blistering in both fluids. The overall rankings of the coatings are summarized below:

	Simulated Accumulator Conditions	
Coating	Catapult	Arresting Gear
Tribaloy 800	1	1
Nedox	2	3
Selectron Ni-Co	3	4*
Selectron Ni-W	5*	2
Nylon 11	4*	5*

* Unacceptable because of severe corrosive attack.

H. CONCLUSIONS. On the basis of the test results and analyses reported herein, the major conclusions are as follows:

1. From the general point of view the best of the five coatings evaluated is Tribaloy 800; this coating had the best overall performance under both simulated catapult accumulator conditions and arresting gear accumulator conditions.

2. Under simulated catapult accumulator conditions, two coatings, Nedox and Selectron Ni-Co, are rated as less effective than the Tribaloy 800 coating but still acceptable for use in actual applications. Two other coatings, Selectron Ni-W and Nylon 11, are considered unacceptable because of poor corrosion resistance.

3. Under simulated arresting gear accumulator conditions, two coatings, Selectron Ni-W and Nedox, are rated as less effective than the Tribaloy 800 coating but are still acceptable for use in actual applications. Two other coatings, Selectron Ni-Co and Nylon 11, are considered unacceptable primarily because of poor corrosion resistance. The Nylon 11 also exhibited blistering and splitting after the 72-hr wear tests in the arresting gear fluid (MIL-H-5559).

4. The Nylon 11 exhibited good friction and wear properties, but poor coating integrity and bonding were major problems. These problems are not necessarily inherent to the Nylon 11 coating; it is believed that unsatisfactory substrate preparation was the cause of the Nylon 11 coating failures reported herein.

5. Test results indicated that MIL-H-22072 fluid constitutes a more hostile environment that MIL-H-5559. This is evidenced by higher wear rates and appreciably greater corrosion damage in MIL-H-22072 fluid than in MIL-H-5559 fluid. This suggests that MIL-H-22072 fluid might be modified to improve its corrosion inhibiting and lubricity properties.

I. RECOMMENDATIONS. On the basis of the coating evaluation program reported herein, recommendations are as follows:

1. It is recommended that Tribaloy 800, and perhaps Nedox, should be further evaluated in reduced-size or full-scale accumulators under conditions simulating those existing during actual accumulator operations.

2. Additional evaluation of Nylon 11 coatings in corrosion tests and wear tests is recommended using specimens fabricated with particular attention to substrate preparation and coating application procedures.

3. It is recommended that a program be undertaken to improve the corrosion inhibiting and lubricity properties of the MIL-H-22072 hydraulic fluid.

VII. TABLES

TABLE I. IDENTIFICATION OF PHASE I COATINGS

Coating Designation	Vendor	Description
Selectron Ni-W "D" (Code SAS 5710)	Cone Engineering Services Dallas, Texas	Brush plated nickel-tungsten alloy
Selectron Ni-Co (Code SAS 5705)	Cone Engineering Services Dallas, Texas	Brush plated nickel-cobalt alloy
Nedox*	General Magnaplate Corp. Linden, New Jersey	Electrodeposited porous nickel alloy infused with poly-tetrafluroethylene (TFE)
Nye-Kote	Electro-Coatings Inc. Houston, Texas	Electroless nickel
Diamondised	Electro-Coatings Inc. Houston, Texas	Electroless nickel-diamond composite
Tribaloy 800	HiTem Co. Hicksville, New York	Plasma sprayed Tribaloy 800 sealed with epoxy
LW-11B	Union Carbide Corp. Houston, Texas	Plasma sprayed 88% WC, 12% Co sealed with epoxy
Nylon 11 (A)	F. W. Gartner Co. (wirespray) Houston, Texas The Donwell Co. (Nylon 11) Manchester, Connecticut	Nylon 11 over wire-sprayed aluminum and Rislan Primer P
Nylon 11 (B)	F. W. Gartner Co. (plasma) Houston, Texas The Donwell Co. (Nylon 11) Manchester, Connecticut	Nylon 11 over plasma-sprayed nickel aluminide and Rilsan Primer P

TABLE I. IDENTIFICATION OF PHASE I COATINGS (CONT'D)

Coating Designation	Vendor	Description
Hytrel	E. I. DuPont de Nemours & Co. Wilmington, Delaware	DuPont Hytrel Polyester resin

* Specimens included Nedox C and Nedox S coatings which are identical in composition but undergo slightly different processing. No distinction between the coatings was made in the corrosion tests. Only the Nedox C coating was subjected to wear tests.

TABLE II. IDENTIFICATION OF
PHASE II COATINGS

Coating Designation	Vendor	Description
Selectron Ni-W "D" (Code SAS 5710)	Cone Engineering Services Dallas, Texas	Brush plated nickel-tungsten alloy
Selectron Ni-Co (Code SAS 5705)	Cone Engineering Services Dallas, Texas	Brush plated nickel-cobalt alloy
Nedox	General Magnaplate Corp. Linden, New Jersey	Electrodeposited porous nickel alloy infused with poly-tetrafluoroethylene (TFE)
Tribaloy 800	HiTem Co. Hicksville, New York	Plasma sprayed Tribaloy 800 sealed with epoxy
Nylon 11	Metco Inc. (wirespray and seal) Westbury, Long Island New York NADC (Nylon 11) Warminster, Pennsylvania	Nylon 11 (electrostatic spray) over subcoat consisting of wire-spray aluminum, Metcoseal sealant, MIL-P-23377 Primer, and Rilsan 104 Primer

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TABLE III. COATING THICKNESS AND ROUGHNESS OF PHASE I RING SPECIMENS

Coating	Thickness,[a] in.	Surface Roughness, μ in. CLA
Selectron Ni-W	0.0003-0.0006	6-12
Selectron Ni-Co	0.0016-0.0022	8-15
Nedox	0.0011-0.0013	35-50
Nye-Kote	0.0042	30-47
Diamondized	0.0003-0.0007	15-30
Tribaloy 800	0.006-0.008[b]	14-22
LW-11B	0.004-0.005[b]	15-19
Nylon 11-(A)	0.0035-0.0040 Al	-
	0.0026-0.0086 Nylon	25-45
Nylon 11-(B)	0.007-0.008 Ni-Al	-
	0.0016-0.0032 Nylon	30-50
Hytrel	0.002-0.004 Hytrel[c]	-
	0.010-0.015 104 Primer	-

a. Based on OD measurements before and after coating except as noted.
b. Based on microscopic measurement on cross section.
c. Thickness after turning to provide concentricity.

TABLE IV. COATING THICKNESS AND ROUGHNESS OF PHASE II RING SPECIMENS

Coating	Thickness[a], in.	Surface Roughness, μ in. CLA
None	-----	20-45
Selectron Ni-W	0.0014-0.0022	7-15
Selectron Ni-Co	0.0020-0.0036	11-22
Nedox	0.0011	25-30
Tribaloy 800	0.0050-0.0057	20-25
Nylon 11	0.0102-0.0123	40-60

a. Based on diameter measurements before and after coating.

TABLE V. CHARACTERISTICS OF CORROSION SPECIMEN COATINGS

Coating Type	Specimen No.	Thickness, in.(4)	Hardness KHN(1)	Hardness R_c(2)	Hardness 15T(3)	Surface Roughness, μin. CLA
Selectron Ni-W	8M	0.0003	504	47	91	10-26
Selectron Ni-Co	9M	0.0004	519	49	91	12-20
Nedox	4M	0.0011	-	-	91	62-75
Nye-Kote	11M	0.0037	600	43	93	25-45
Diamondized	10M	0.0010	-	-	90	42-47
Tribaloy 800	5M	0.0050	420(6)	41	78(8)	4-12
LW-11B	3M	0.0053	826(6)	64	75(8)	23-34
Nylon 11 (A)	6M	0.0004-0.0024(7) 0.0010-0.0020	N/A	N/A	N/A	93-175
Nylon 11 (B)	7M	0.0067(7) 0.0033	N/A	N/A	N/A	50-75
Hytrel	2M	0.0073(5)	N/A	N/A	N/A	25-35

Notes:

(1) Knoop hardness number measured on metallographic section - (100 gram load).
(2) Converted from Knoop hardness number; approximate values.
(3) Rockwell superficial hardness measured on specimen surface.
(4) Measured in metallographic section.
(5) Average value determined by stripping coating.
(6) 500 g load.
(7) Average thickness only, subcoating excluded.
(8) 15N scale.

TABLE VI. COATING THICKNESS, TAPERED TENSILE AND FATIGUE SPECIMENS

	Tensile Specimens		Fatigue Specimens	
Coating Type	Specimen No.	Coating Thickness, in.	Specimen No.	Coating Thickness, in.
Nedox	T-4-1	0.0004	F-4-1	0.0010
	T-4-2	0.0004	F-4-2	0.0012
	T-4-3	----	F-4-3	0.0018
Tribaloy T-800	T-5-1	0.0052	F-B-1	----
	T-5-2	0.0053	F-B-2	0.0056
	T-5-3	0.0058	----	----
Nylon 11	T-6-1	0.0170	F-6-1	0.0228
	T-6-2	0.0157	F-6-2	0.0204
	T-6-3	----	F-6-3	0.0172
Selectron Ni-W	T-8-1	----	F-8-1	----
	T-8-2	----	F-8-2	0.0026
	T-8-3	0.0033	F-8-3	0.0024
Selectron Ni-Co	T-9-1	----	F-9-1	0.0022
	T-9-2	----	F-9-2	----
	T-9-3	0.0006	F-9-3	0.0018

TABLE VII. WEAR TEST CONDITIONS

Condition	Phase I Tests, Simulated System: Catapult Accumulator	Phase I Tests, Simulated System: Arresting Gear Accumulator	Phase II Tests, Simulated System: Catapult Accumulator	Phase II Tests, Simulated System: Arresting Gear Accumulator
Normal load, lb	8	8	8	8
Fluid temperature, °F	180	180	160	180
Cycle sequence				
Time forward, sec	10	3.8	10	3.8
Time off, sec	3	0	3	0
Time reverse, sec	10	3.8	10	3.8
Time off, sec	3	0	3	0
Maximum speed, rpm	65	800	65	800
Maximum sliding speed, fpm	25.5	313	25.5	313
Test duration, hr	24	24	72	72
Total cycles	3,323	11,368	9.970	34,100
Total cylinder revolutions	72,000	955,000	216,000	2,865,000
Total sliding distance, ft	28,300	375,000	84,900	1,125,000
Test fluid	MIL-H-22072	MIL-H-5559	MIL-H-22072	MIL-H-5559
Block material	Bronze	Aluminum	Bronze	Aluminum

TABLE VIII. SUMMARY OF PHASE I FRICTION AND WEAR TESTS UNDER SIMULATED CATAPULT ACCUMULATOR CONDITIONS

Ring Coating	Average Coefficient of Friction at Indicated Time: 0 hr	1-24 hr	Average Weight Change, g: Block	Ring	Remarks
None					
Test 19	0.15	0.01	-0.0103	+0.0067	—
Test 20	0.13	0.02	+0.0019	+0.0067	—
Avg	0.14	0.02	-0.0042	+0.0067	—
Diamondized					
Test 21	0.09	0.03	-0.0199	-0.0006	—
Test 22	0.07	0.02	-0.0279	-0.0005	—
Avg	0.08	0.02	-0.0239	-0.0006	—
Selectron Ni-W					
Test 23	0.08	0.02	-0.0027	-0.0003	—
Test 24	0.07	a	-0.0006	-0.0004	—
Test 29	0.08	0.02	-0.0019	-0.0035	—
Test 30	0.06	0.01	-0.0023	-0.0016	—
Avg	0.07	0.02	-0.0019	-0.0014	—
LW-11B					
Test 25	0.12	0.02	-0.0114	-0.0063	—
Test 26	0.12	0.04	-0.0044	-0.0024	—
Avg	0.12	0.03	-0.0079	-0.0044	—
Nylon 11-A					
Test 27	0.04	0.01	+0.0006	+0.0065	—
Test 28	0.03	—	-0.0199	-0.1331	Coating off at 1 hr
Avg	0.04	0.01	-0.0096	-0.0633	Wear projected to 24 hr
Nylon 11-B					
Test 31	0.03	a	+0.0002	+0.0150	—
Test 32	0.04	0.01	0	+0.0171	—
Avg	0.04	0.01	+0.0001	+0.0160	—
T-800					
Test 33	0.02	0.02	-0.0038	+0.0154	—
Test 34	0.03	0.02	-0.0081	+0.0151	—
Avg	0.02	0.02	-0.0060	+0.0152	—

TABLE VIII. SUMMARY OF PHASE I FRICTION AND WEAR TESTS UNDER SIMULATED CATAPULT ACCUMULATOR CONDITIONS (Cont'd)

Ring Coating	Average Coefficient of Friction at Indicated Time		Average Weight Change, g		Remarks
	0 hr	1-24 hr	Block	Ring	
Selectron Ni-Co					
Test 35	0.04	0.02	-0.0036	+0.0004	—
Test 36	0.03	0.01	-0.0004	+0.0005	—
Avg	0.04	0.02	-0.0020	+0.0004	—
Nye-Kote					
Test 37	0.16	0.05	-2.9744	-0.0224	17-hr test
Test 38	0.17	0.06	-2.7422	-0.0087	17-hr test
Avg	0.16	0.06	-4.0352	-0.0220	Wear projected to 24 hr
Nedox					
Test 39	0.13	0.04	-0.5008	-0.0002	—
Test 40	0.15	0.03	-0.1048	-0.0002	—
Avg	0.14	0.04	-0.3028	-0.0002	—
Hytrel					
Test 57	a	0.05	-0.0263	-0.3229	21-hr test
Test 58	a	0.04	-0.0003	-0.1878	5-hr test
Avg	a	0.04	-0.0158	-0.6345	Wear projected to 24 hr

a. Recorder malfunction.

TABLE IX. PREFERENTIAL OVERALL RANKING OF COATINGS BASED ON PHASE I SIMULATED CATAPULT ACCUMULATOR CONDITIONS

Coating	Weighted Rankings: Ring Wear	Block Wear	Friction	Weighted Ranking Total	Overall Preferential Ranking
Nylon 11-B	3	2	2	7	1
T-800	6	8	1	15	2
Selectron Ni-Co	9	6	3	18	3
Selectron Ni-W	18	4	4	26	4
Diamondized	15	16	6	37	5
Nedox	12	18	8	38	6
LW-11B	21	10	7	38	6
Nylon 11-A	27	12	2	41	7
Hytrel	21	16	4	41	7
Nye-Kote	24	20	9	53	8

TABLE X. SUMMARY OF PHASE I FRICTION AND WEAR TESTS UNDER SIMULATED ARRESTING GEAR CONDITIONS

Ring Coating	Average Coefficient of Friction at Indicated Time: 0 hr	Average Coefficient of Friction at Indicated Time: 1-24 hr	Weight Change, g: Block	Weight Change, g: Ring	Remarks
None					
Test 7	0.22	0.02	-0.0074	-0.0077	—
Test 8	0.18	0.02	-0.0130	-0.0101	—
Avg	0.20	0.02	-0.0102	-0.0089	—
Diamondized					
Test 9	0.15	a	-0.0606	-0.0027	1.1-hr test
Test 10	0.31	a	-0.3132	-0.0717	1.1-hr test
Test 11	0.18	0.05	-0.6907	-0.0066	8.8-hr test
Test 12	0.29	0.20	-0.5694	-0.1043	2.0-hr test
Test 51	0.33	0.03	-1.0689	-0.0812	5.0-hr test
Test 52	0.32	0.04	-1.2160	+0.0606	5.0-hr test
Avg	0.26	0.08	-4.6399	-0.4986	Wear projected to 24 hr.
Selectron Ni-W					
Test 13	0.25	0.01	-0.0324	-0.0173	—
Test 14	0.68	0.02	-0.0105	-0.0129	—
Avg	0.47	0.02	-0.0214	-0.0151	—
LW-11B					
Test 16	0.26	0.04	-0.2585	-0.0477	—
Test 17	0.27	0.02	-0.2036	-0.0162	—
Avg	0.26	0.03	-0.2310	-0.0320	—
Nylon 11 (A)					
Test 45	a	0.01	+0.0012	+0.0305	—
Test 46	0.03	—	-0.0603	-0.2511	1-hr test
Avg	0.03	0.01	-0.7230	-2.9980	Wear projected to 24 hr.
Nylon 11 (B)					
Test 47	0.06	0.01	+0.0034	+0.0371	—
Test 48	0.08	0.05	-0.3252	-0.2202	6.5-hr test
Avg	0.07	0.03	-0.5986	-0.3880	Wear projected to 24 hr.
T-800					
Test 49	0.21	0.02	-0.0169	+0.0068	—
Test 50	0.17	0.03	-0.0085	+0.0016	—
Avg	0.19	0.02	-0.0127	+0.0042	—

TABLE X. SUMMARY OF PHASE I FRICTION AND WEAR TESTS UNDER SIMULATED ARRESTING GEAR CONDITIONS (Cont'd)

Ring Coating	Average Coefficient of Friction at Indicated Time		Weight Change, g		Remarks
	0 hr	1-24 hr	Block	Ring	
Selectron Ni-Co					
Test 43	0.12	0.02	-0.0103	-0.0295	—
Test 44	0.20	0.02	-0.0136	-0.0313	—
Avg	0.16	0.02	-0.0120	-0.0304	—
Nye-Kote					
Test 53	0.35	[0.29][b]	-1.5929	-0.0773	30-m test
Test 54	0.36	[0.36][b]	-1.5694	-0.1020	30-m test
Avg	0.36	[0.32][b]	-75.8928	-6.8036	Wear projected to 24 hr.
Nedox					
Test 41	0.33	0.02	-0.1258	-0.0052	—
Test 42	0.28	0.02	-0.0982	-0.0090	—
Avg	0.30	0.02	-0.1120	-0.0071	—
Hytrel					
Test 55	0.13	0.04[c]	-0.7143	-0.3054	16-hr test
Test 56	0.22	0.07[d]	-0.2605	-0.2792	16-hr test
Avg	0.18	0.06	-0.7311	-0.4385	Wear projected to 24 hr.

a. Recorder malfunction.
b. Average coefficient of friction during 5-30 min.
c. Average coefficient of friction during 1-9 hr (time during which coating was intact).
d. Average coefficient of friction during 1-1.9 hr (time during which coating was intact).

TABLE XI. PREFERENTIAL OVERALL RANKING OF COATINGS BASED ON PHASE I TESTS SIMULATING ARRESTING GEAR CONDITIONS

Coating	Weighted Rankings Ring Wear	Block Wear	Friction	Weighted Ranking Total	Overall Preferential Ranking
T-800	3	4	5	12	1
Selectron Ni-Co	12	2	3	17	2
Nedox	6	8	8	22	3
Selectron Ni-W	9	6	10	25	4
LW-11B	15	10	6	31	5
Nylon 11 (B)	18	12	2	32	6
Hytrel	21	16	4	41	7
Nylon 11 (A)	27	14	1	42	8
Diamondized	24	18	7	49	9
Nye-Kote	30	20	9	59	10

TABLE XII. CORRELATION OF COATING SURFACE ROUGHNESS AND BLOCK WEAR IN PHASE I TESTS

Coating	Average Surface Roughness, μin.	Block 24-hr Average Weight Loss, g	
		Catapult	Arresting
Selectron Ni-W	9	-0.0019	-0.0214
Selectron Ni-Co	11	-0.0020	-0.0120
T-800	18	-0.0060	-0.0127
LW-11B	17	-0.0079	-0.2310
Nedox	47	-0.3028	-0.1120
Diamondized	22	-0.0239	-4.6399
Nye-Kote	38	-4.0352	-75.8928

TABLE XIII. SUMMARY OF PHASE II FRICTION AND WEAR TESTS UNDER SIMULATED CATAPULT ACCUMULATOR CONDITIONS

Ring Coating	Average Coefficient of Friction at Indicated Time: 0 hr	1-72 hr	Weight Change, g: Block	Ring	Average Ring Wear Volume, in.^{3}
None					
Test 3	0.14	0.04	-0.0200	+0.0016	—
Test 4	0.06	0.01	-0.0202	+0.0014	—
Test 5	0.16	0.09	-0.0063	-0.0012	—
Test 6	0.05	0.02	-0.0053	-0.0043	—
Test 7	0.10	0.04	-0.0306	-0.0003	—
Test 8	0.02	0.02	-0.0070	+0.0032	—
Avg	0.11	0.04	-0.0149	+0.0001	—
Selectron Ni-W					
Test 9	0.09	0.03	-0.0060	-0.0110	—
Test 10	0.02	0.02	-0.0046	-0.0098	—
Avg	0.06	0.02	-0.0053	-0.0104	0.000061
Selectron Ni-Co					
Test 21	0.14	0.03	-0.0058	-0.0199	—
Test 22	0.09	0.04	-0.0051	-0.0308	—
Avg	0.12	0.04	-0.0054	-0.0254	0.000174
Nedox					
Test 11[a]	0.19[a]	0.11[a]	-0.7088[a]	-0.0049[a]	—
Test 12[a]	0.04[a]	0.07[a]	-0.8615[a]	-0.0033[a]	—
Test 23	0.11	0.03	-1.4484	-0.0042	—
Test 24	0.07	0.01	-0.3352	-0.0023	—
Avg	0.09	0.02	-0.8918	-0.0032	0.000023
Tribaloy 800					
Test 17	0.03	0.02	-0.0478	-0.0066	—
Test 18	0.08	0.02	-0.0791	-0.0155	—
Avg	0.06	0.02	-0.0634	-0.0110	0.000079
Nylon 11 (B)					
Test 31	0.07	0.01	-0.0059	+0.0157	—
Test 32	0.06	0.01	-0.0041	+0.0219	—
Avg	0.06	0.01	-0.0050	+0.0188	—

a. 1.5 hr test on faulty coating, results not included in averages.

TABLE XIV. PREFERENTIAL OVERALL RANKING OF COATINGS BASED ON PHASE II SIMULATED CATAPULT ACCUMULATOR CONDITIONS

Coating	Weighted Rankings Ring Wear	Block Wear	Friction	Weighted Ranking Total	Overall Preferential Ranking
Selectron Ni-W	6	4	2	12	1
Nedox	3	10	3	16	2
Nylon 11 (B)	15	2	1	18	3
Tribaloy 800	9	8	2	19	4
Selectron Ni-Co	12	6	4	22	5

TABLE XV. SUMMARY OF PHASE II FRICTION AND WEAR TESTS UNDER SIMULATED ARRESTING GEAR CONDITIONS

Ring Coating	Average Coefficient of Friction at Indicated Time: 0 hr	1-72 hr	Weight Change, g: Block	Ring	Average Ring Wear Volume, $in.^3$
None					
Test 1	0.16	0.05	-0.0730	-0.0200	—
Test 2	0.15	0.04	-0.0620	-0.0110	—
Test 19	0.27	0.02	-0.0736	-0.0141	—
Avg	0.19	0.04	-0.0695	-0.0150	0.000117
Selectron Ni-W					
Test 13	0.16	0.02	-0.0130	-0.0568	—
Test 14	0.04	0.01	-0.0512	-0.0648	—
Test 20	0.15	0.01	-0.0762	-0.0678	—
Avg	0.10	0.01	-0.0468	-0.0631	0.000368
Selectron Ni-Co					
Test 25	0.16	0.01	-0.0135	-0.0460	—
Test 26	0.10	0.01	-0.0352	-0.0590	—
Test 29	0.14	0.01	-0.0360	-0.0542	—
Avg	0.13	0.01	-0.0282	-0.0531	0.000363
Nedox					
Test 27	0.30	0.01	-0.0897	-0.0413	—
Test 28	0.24	0.01	-0.1211	-0.0472	—
Avg	0.27	0.01	-0.1054	-0.0443	0.000325
Tribaloy 800					
Test 15	0.15	0.02	-0.0732	-0.0118	—
Test 16	0.11	0.01	-0.0849	-0.0148	—
Test 30	0.21	0.02	-0.0894	-0.0120	—
Avg	0.16	0.02	-0.0825	-0.0129	0.000093
Nylon 11 (B)					
Test 33	0.07	0.01	-0.0059	+0.0157[a]	—
Test 34	0.06	0.01	-0.0041	+0.0219[b]	—
Avg	0.06	0.01	-0.0050	+0.0188	—

a. Coating broken.
b. Coating blistered.

TABLE XVI. PREFERENTIAL OVERALL RANKING OF COATINGS BASED ON PHASE II SIMULATED ARRESTING GEAR CONDITIONS

	Weighted Rankings			Weighted	Overall
Coating	Ring Wear	Block Wear	Friction	Ranking Total	Preferential Ranking
Tribaloy 800	3	8	4	15	1
Selectron Ni-Co	9	4	3	16	2
Nylon 11	15	2	1	18	3
Selectron Ni-W	12	6	2	20	4
Nedox	6	10	5	21	5

TABLE XVII. COMPARISON OF WEAR TEST RESULTS FROM PHASES I AND II

Coating	Simulated Catapult Accumulator Tests — Average Wear Rate, 10^{-10} in^3/rev.				Simulated Arresting Gear Accumulator Tests — Average Wear Rate, 10^{-10} in^3/rev.			
	Block[a]		Ring[b]		Block[c]		Ring[b]	
	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II
None	4.24	5.02	0[d]	0[d]	2.36	5.35	0.72	0.41
Selectron Ni-W	1.92	1.78	1.13	2.82	4.93	3.59	0.92	1.28
Selectron Ni-Co	2.02	1.82	0[d]	8.06	2.78	2.16	2.17	1.26
Nedox	306.	300.	0.21	1.06	25.8	8.11	0.54	1.13
Tribaloy 800	6.06	21.4	0[d]	3.66	2.93	6.34	0[d]	0.32
Average for all coatings:	64.0	66.0	0.27	3.12	7.75	5.11	0.87	0.88

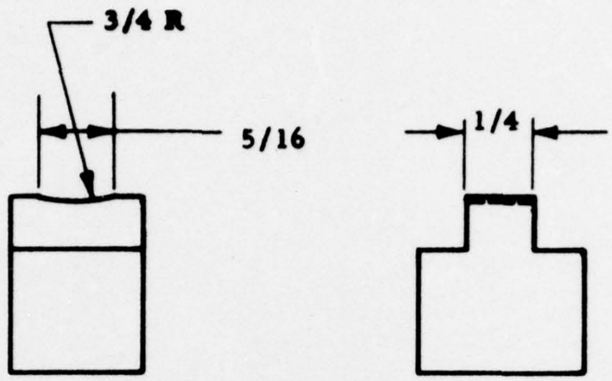
a. Specific weight of bronze block: 0.303 lb/in^3.
b. Specific weights: steel, 0.283 lb/in^3; Ni-W, 0.378 lb/in^3; Ni-Co, 0.322 lb/in^3; Nedox, 0.30 lb/in^3; Tribaloy, 0.305 lb/in^3.
c. Specific weight of aluminum block: 0.100 lb/in^3.
d. Average ring weight gain.

TABLE XVIII. OVERALL RATING OF COATINGS

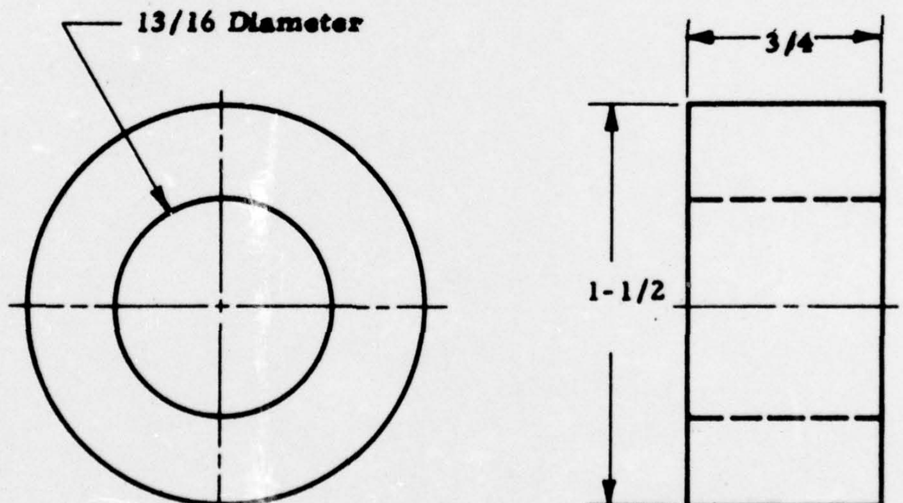
Coating	Simulated Catapult Accumulator Tests			Simulated Arresting Gear Accumulator Tests		
	Wear Rating	Corrosion Rating	Overall Rating	Wear Rating	Corrosion Rating	Overall Rating
Tribaloy 800	4	1	1	1	1	1
Nedox	2	2	2	5	2	3
Selectron Ni-Co	5	3	3	2	5*	4
Selectron Ni-W	1	5*	5	4	3	2
Nylon 11	3	4*	4	3	4*	5

* Unacceptable because of severe corrosive attack.

VIII. FIGURES

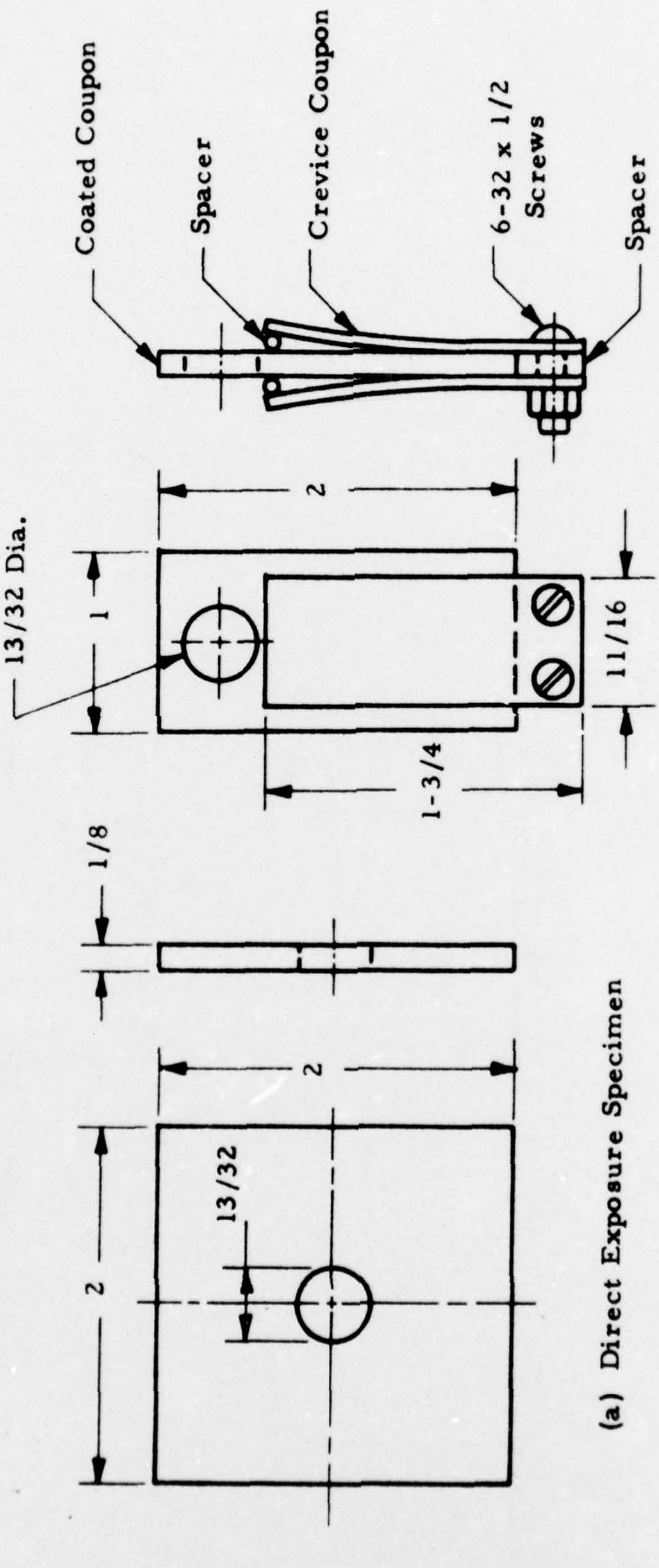


Block Specimen



Ring Specimen

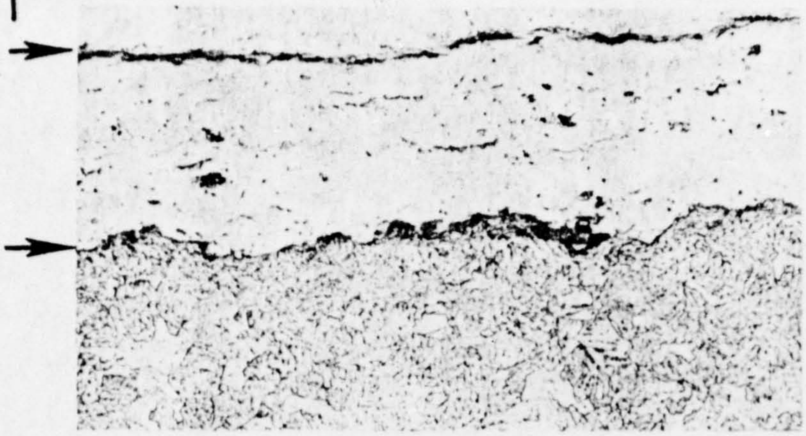
FIGURE 1. WEAR SPECIMENS.



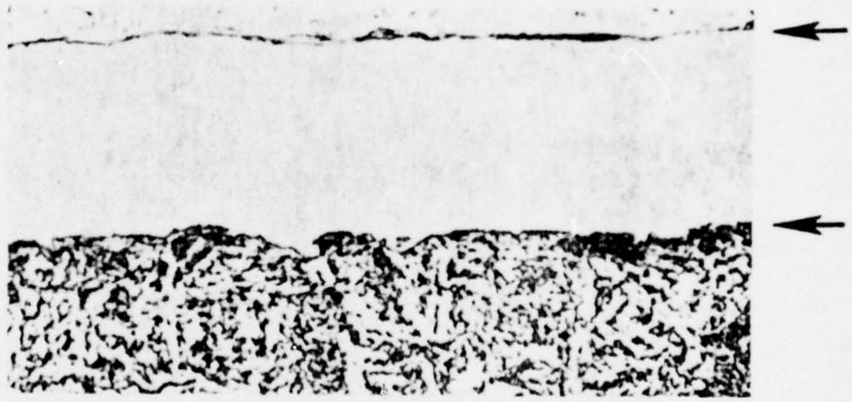
(a) Direct Exposure Specimen

(b) Crevice Corrosion Assembly

FIGURE 2. CORROSION SPECIMENS.



(a)
LW-11B. 200X.
t = 0.0053 in.

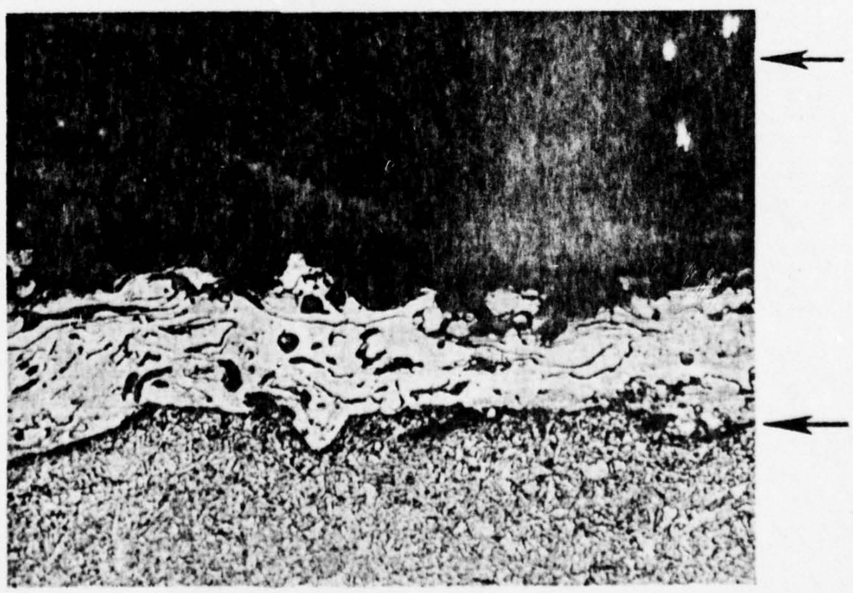


(b)
Nedox. 1000X.
t = 0.0011 in.

(c)
Tribaloy 800. 500X.
t = 0.0050 in.

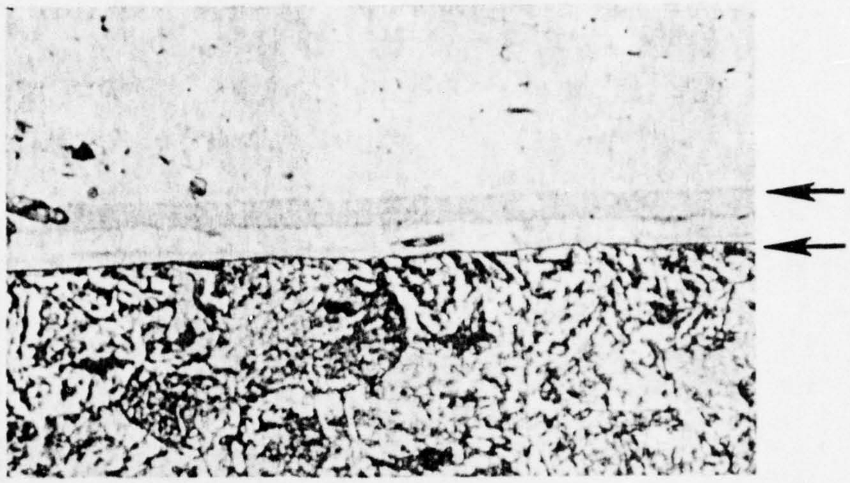
FIGURE 3. PHOTOMICROGRAPHS OF METALLOGRAPHIC CONTROL SPECIMENS. Etchant: Nital.

(d) Nylon 11(A). 500X.
t = 0.005 in. (total).

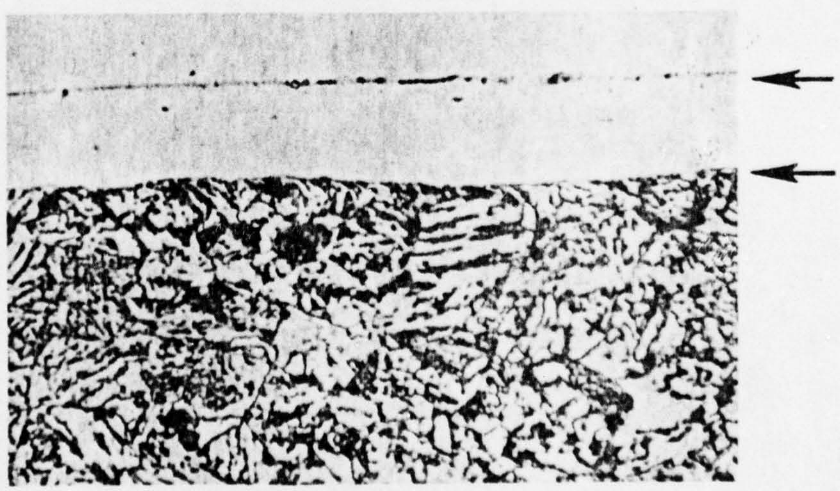


(e) Nylon 11(B). 200X.
t = 0.020 in. (total).

FIGURE 3. (cont'd). PHOTOMICROGRAPHS OF METALLOGRAPHIC CONTROL SPECIMENS. Etchant: Nital.

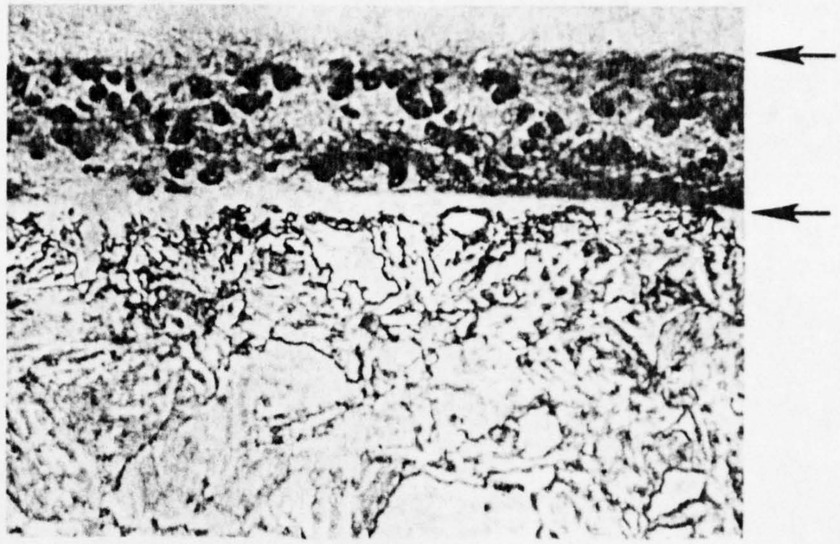


(f) Selectron Ni-W. 1000X.
t = 0.0003 in.

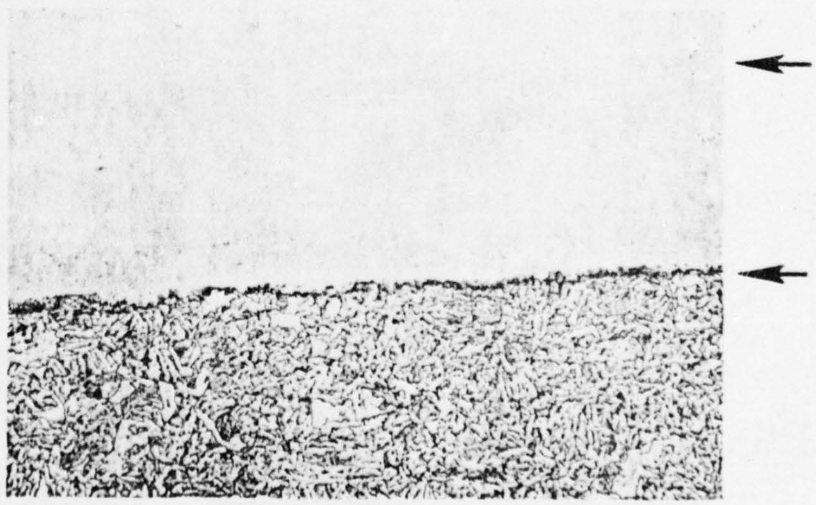


(g) Selectron Ni-Co. 1000X.
t = 0.0005 in.

FIGURE 3. (cont'd). PHOTOMICROGRAPHS OF METALLOGRAPHIC CONTROL SPECIMENS. Etchant: Nital.



(h) Diamondized. 1000X.
t = 0.0010 in.



(i) Nye-Kote. 300X.
t = 0.0037 in.

FIGURE 3. (cont'd). PHOTOMICROGRAPHS OF METALLOGRAPHIC CONTROL SPECIMENS. Etchant: Nital.

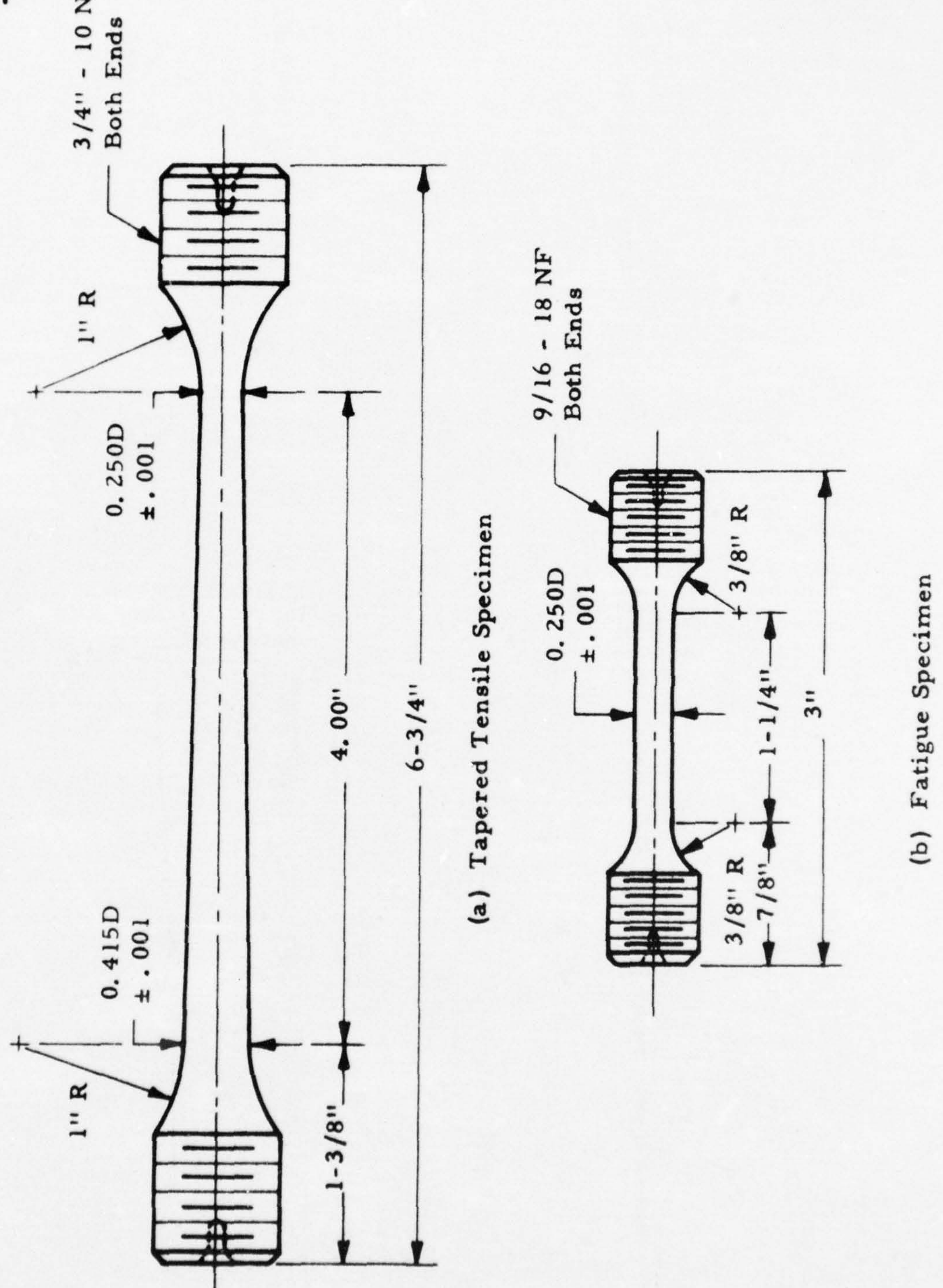


FIGURE 4. MECHANICAL TEST SPECIMENS.

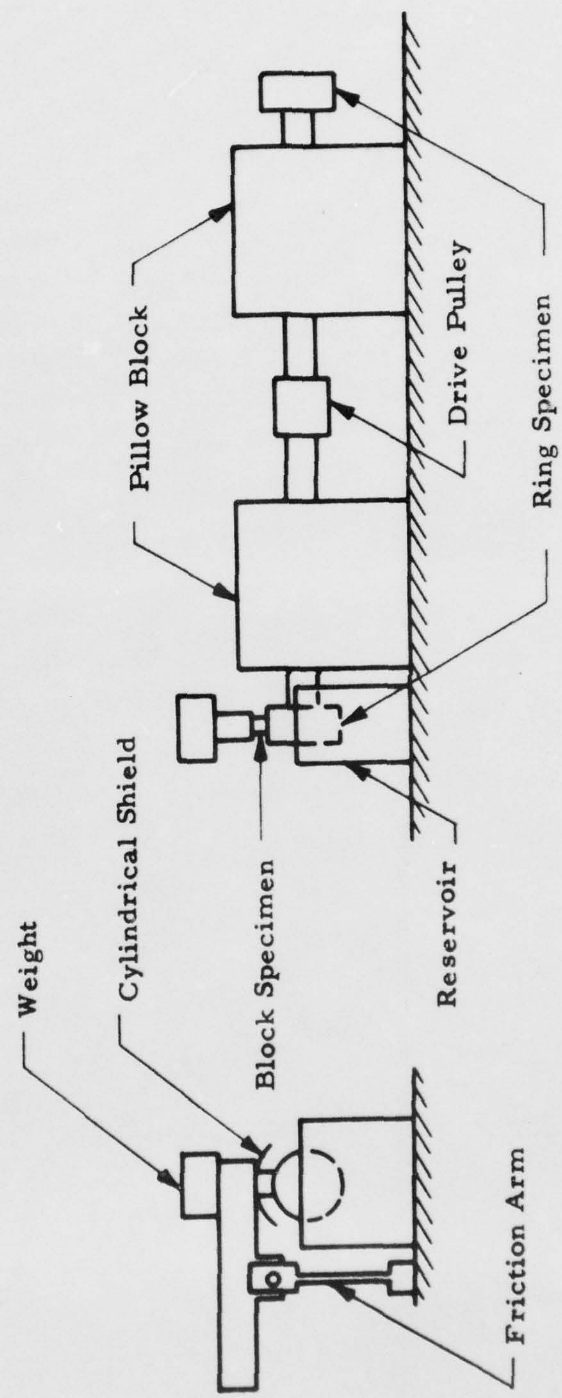


FIGURE 5. BLOCK ON RING TEST RIG.

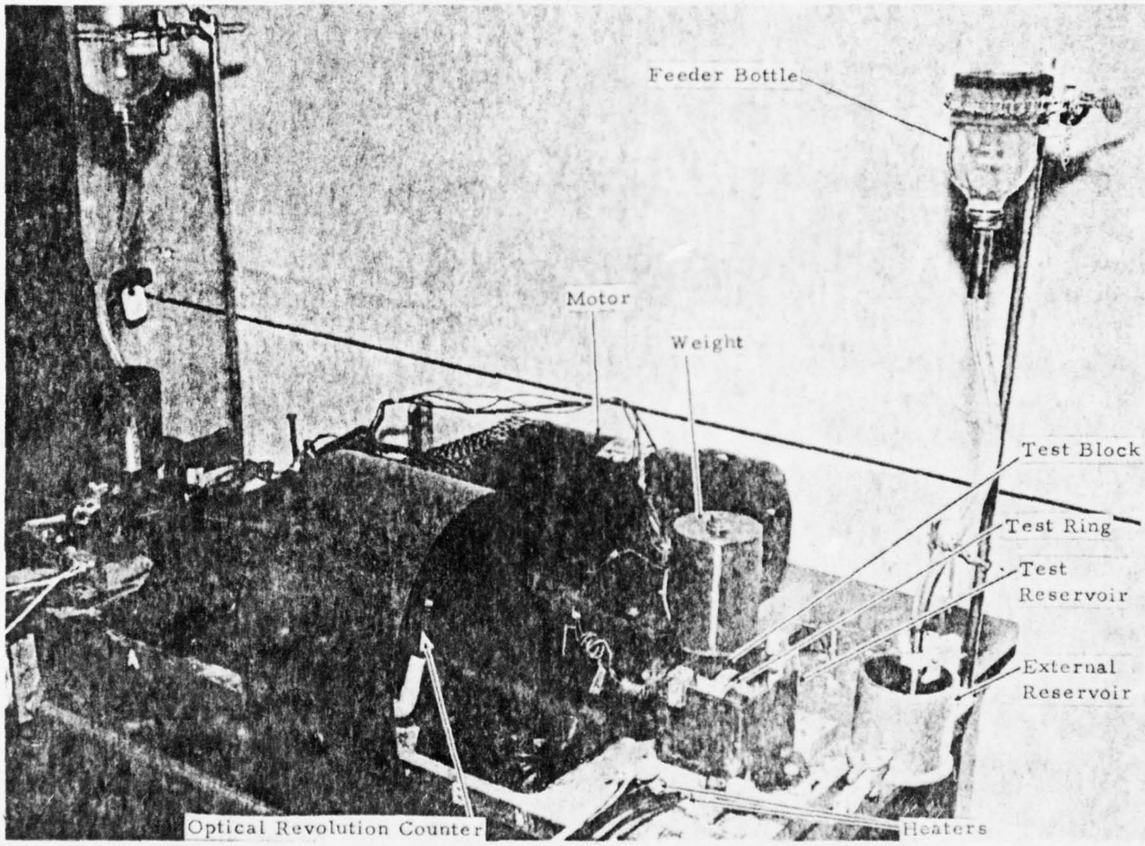
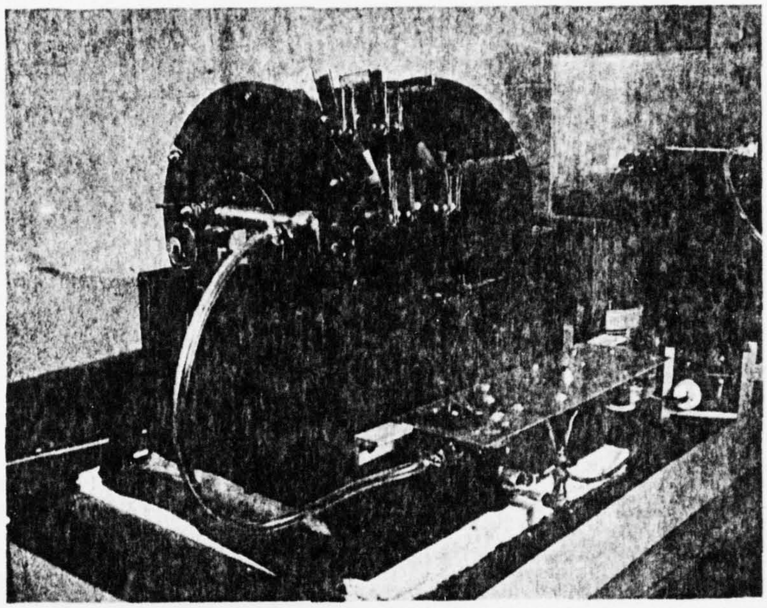


FIGURE 6. PHOTOGRAPH OF BLOCK ON RING TEST RIG



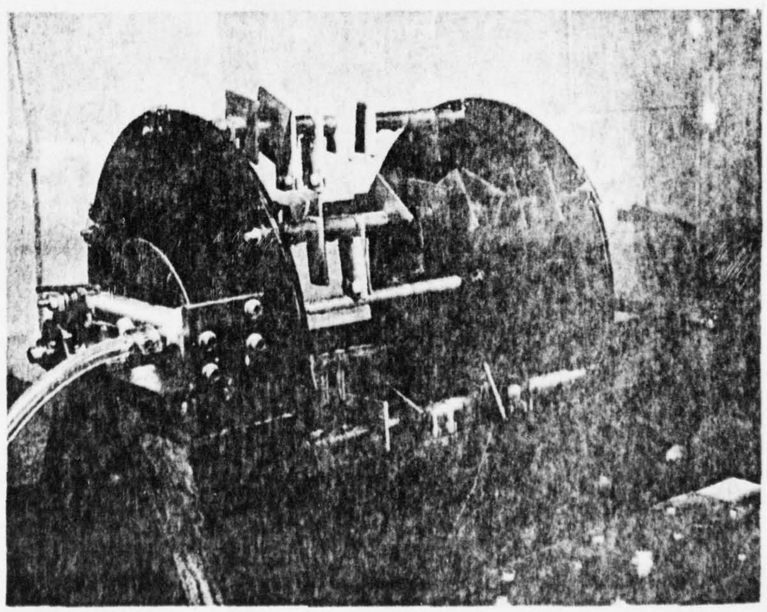


FIGURE 7. ALTERNATE IMMERSION CORROSION TEST APPARATUS WITH COVER REMOVED

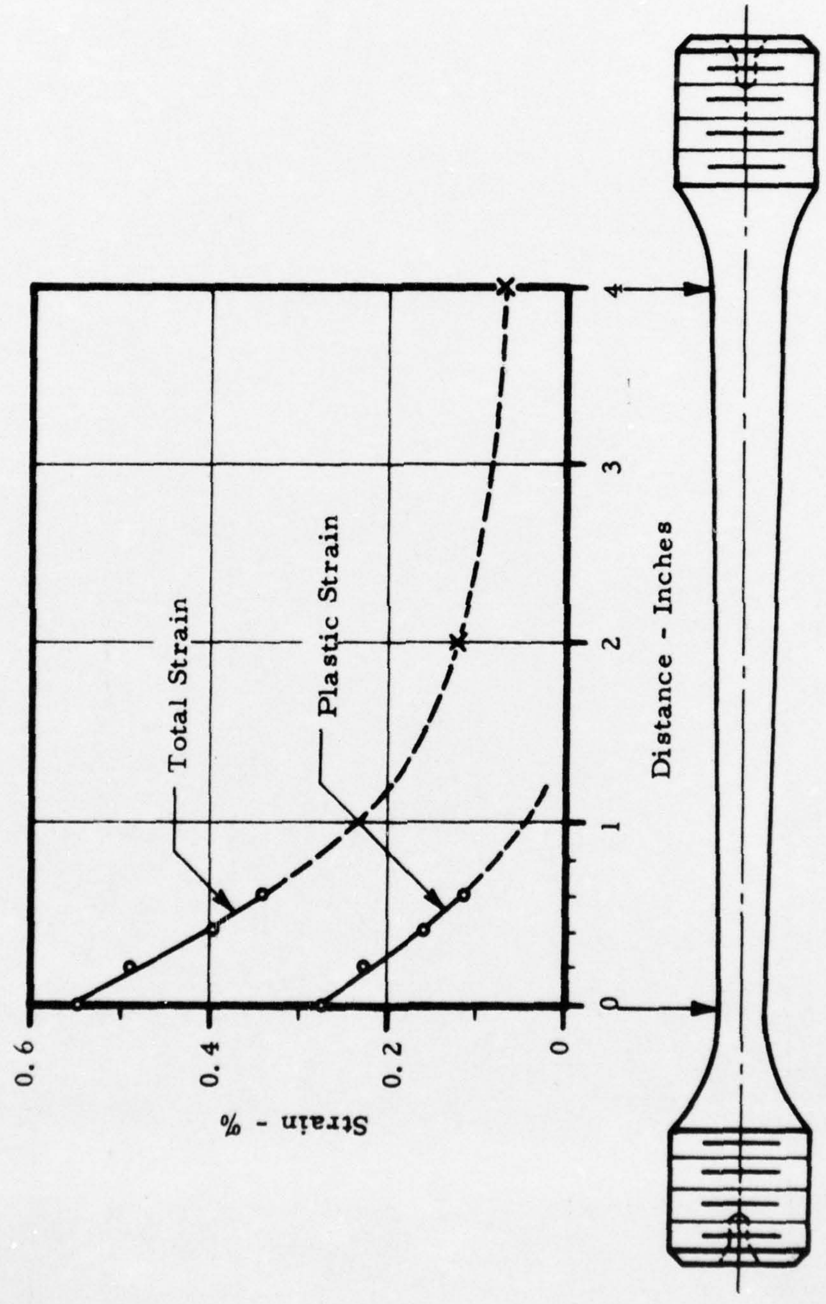


FIGURE 8. TAPERED TENSILE CALIBRATION TEST

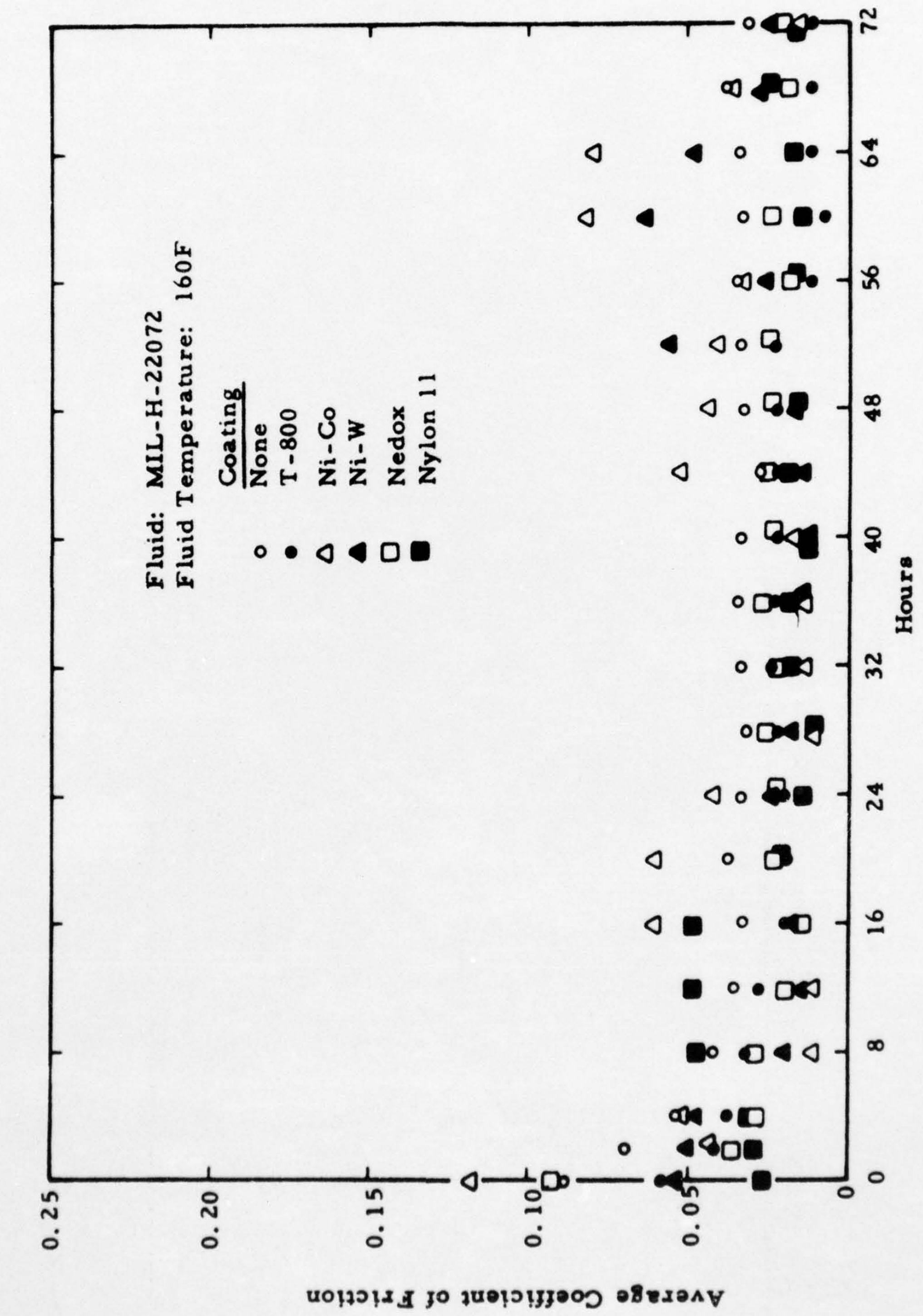


FIGURE 9. FRICTION VERSUS TIME IN SIMULATED CATAPULT ACCUMULATOR WEAR TESTS

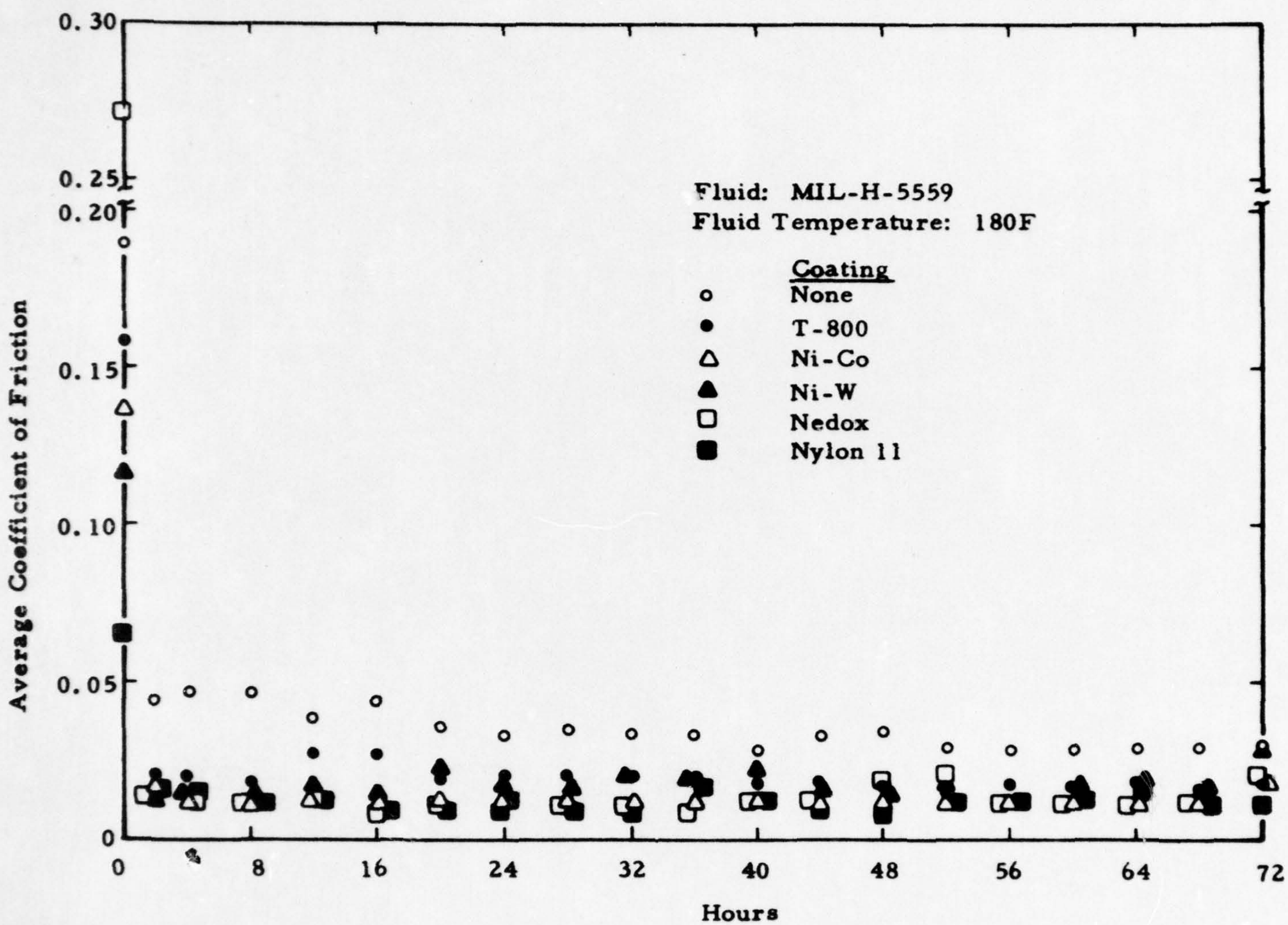


FIGURE 10. FRICTION VERSUS TIME IN SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TESTS

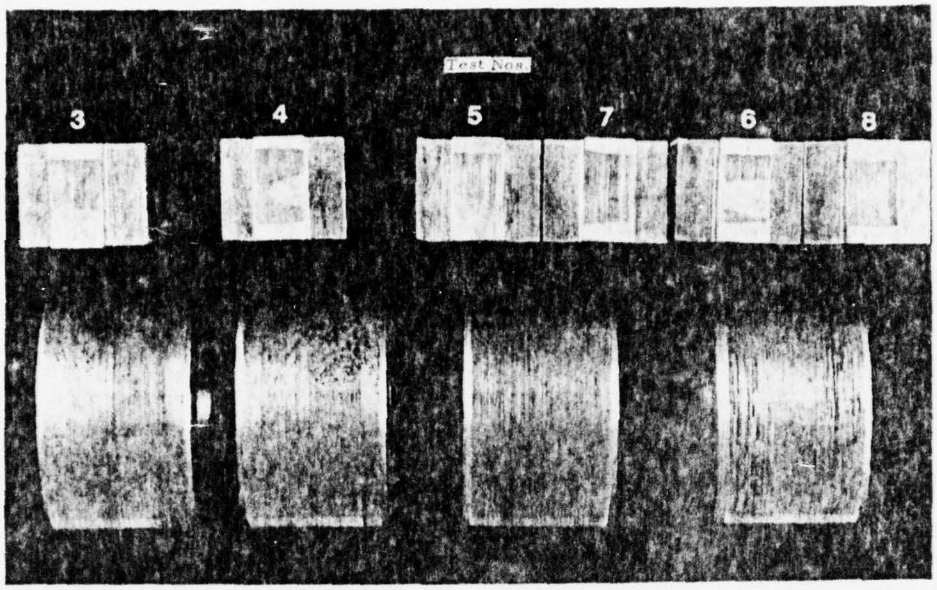


FIGURE 11. BRONZE BLOCKS AND UNCOATED STEEL RINGS AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TESTS

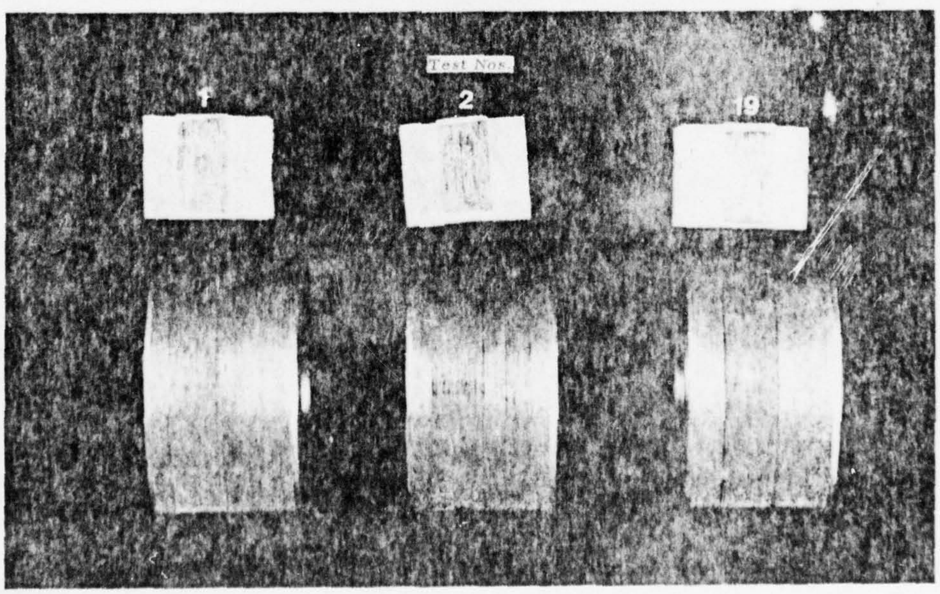


FIGURE 12. ALUMINUM BLOCKS AND UNCOATED STEEL RINGS AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TESTS

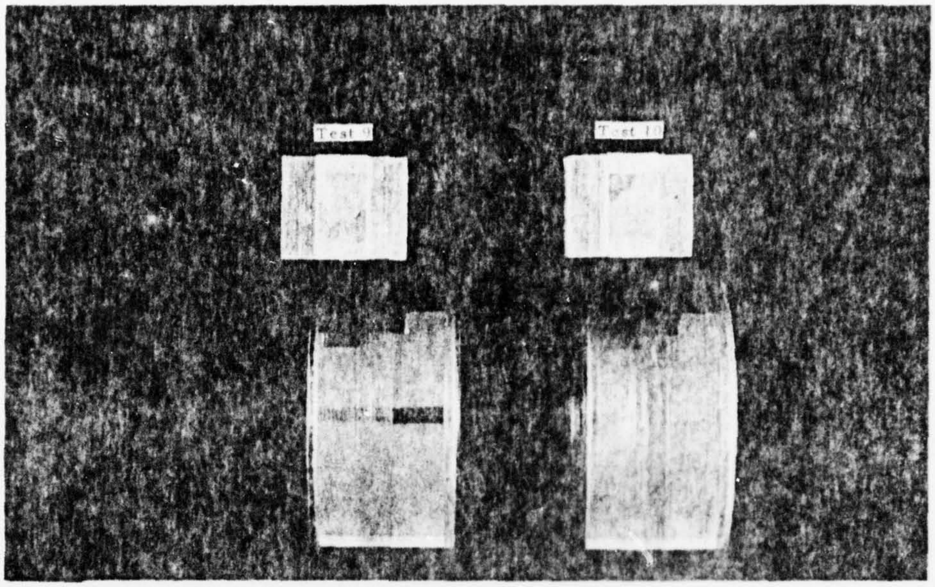


FIGURE 13. BRONZE BLOCKS AND SELECTRON Ni-W COATED STEEL RINGS AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TESTS

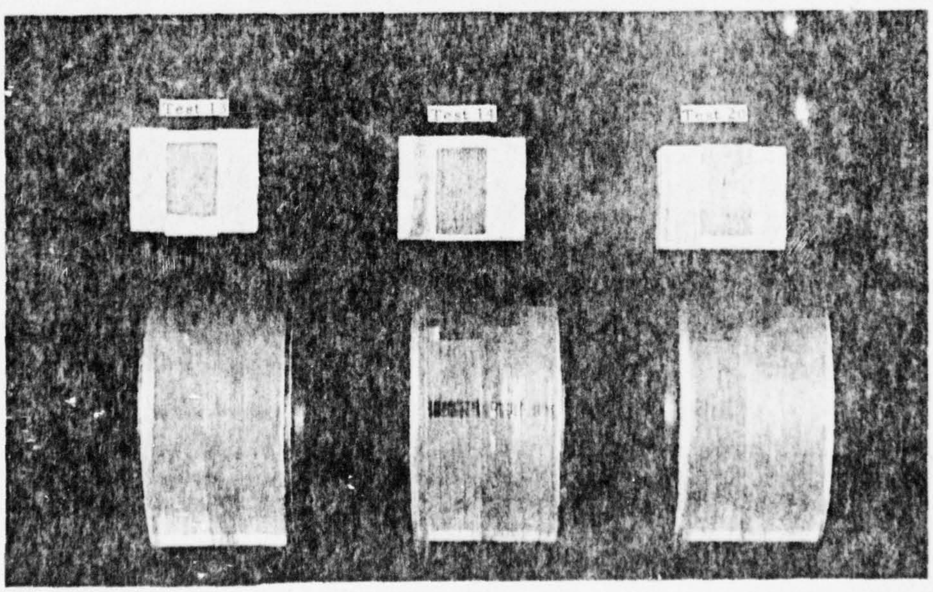


FIGURE 14. ALUMINUM BLOCKS AND SELECTRON Ni-W COATED STEEL RINGS AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TESTS

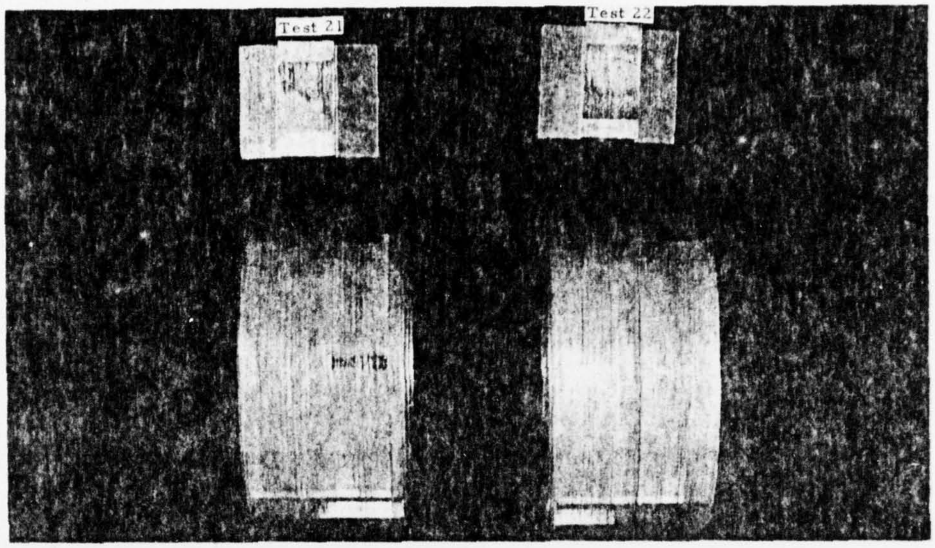


FIGURE 15. BRONZE BLOCKS AND SELECTRON Ni-Co COATED STEEL RINGS AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TESTS

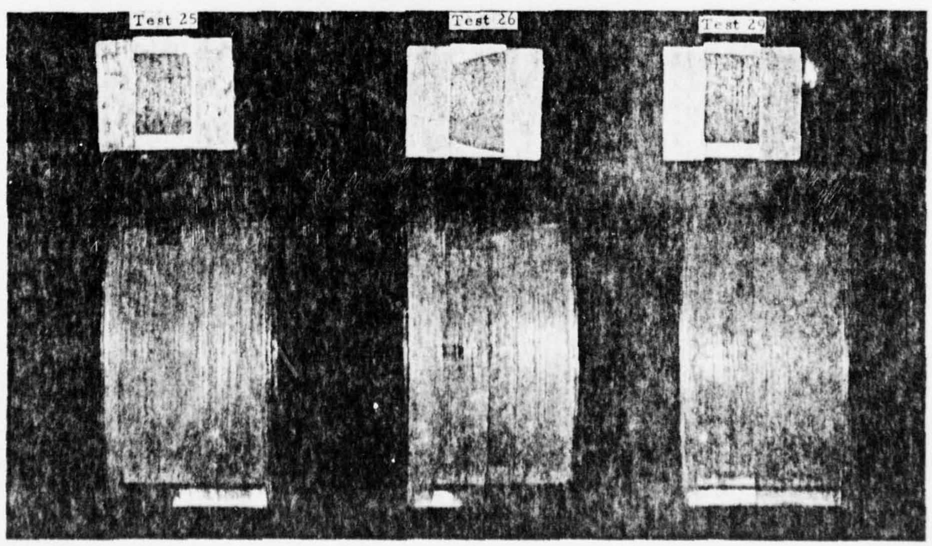


FIGURE 16. ALUMINUM BLOCKS AND SELECTRON Ni-Co COATED STEEL RINGS AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TESTS

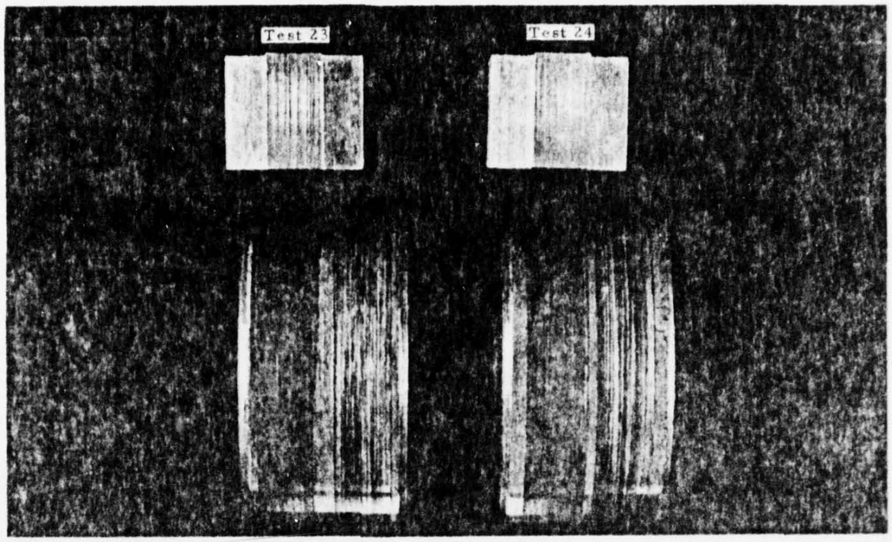


FIGURE 17. BRONZE BLOCKS AND NEDOX COATED STEEL RINGS AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TESTS

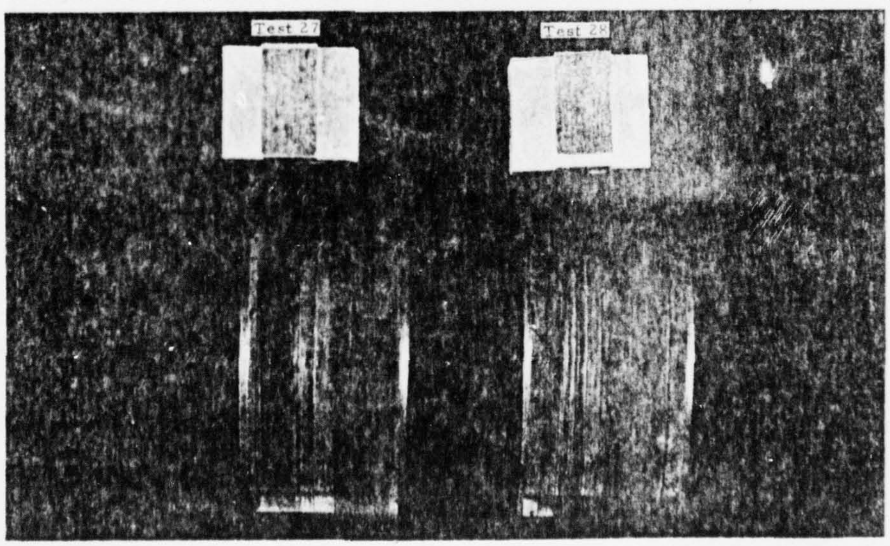


FIGURE 18. ALUMINUM BLOCKS AND NEDOX COATED STEEL RINGS AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TESTS

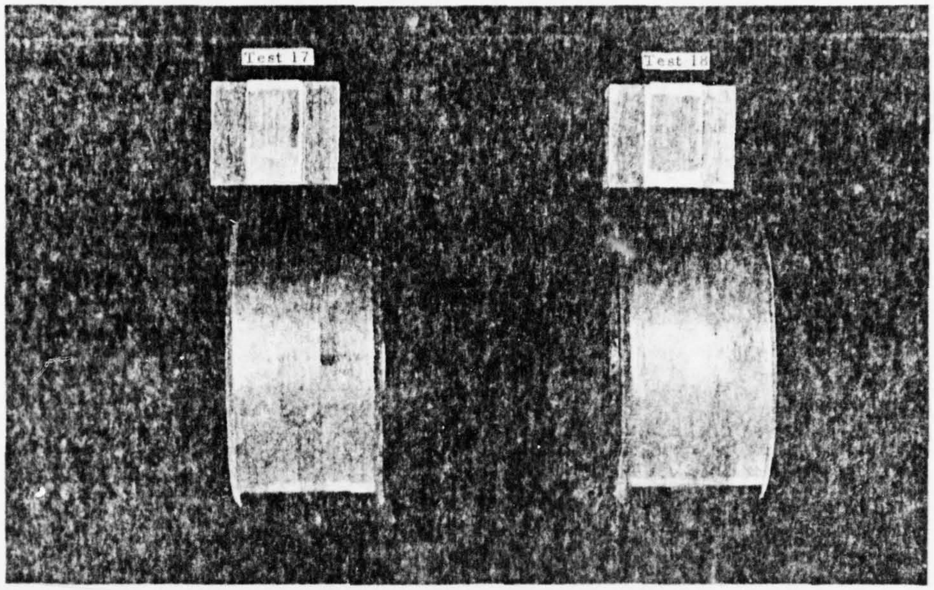


FIGURE 19. BRONZE BLOCKS AND TRIBALOY 800 COATED STEEL RINGS AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TESTS

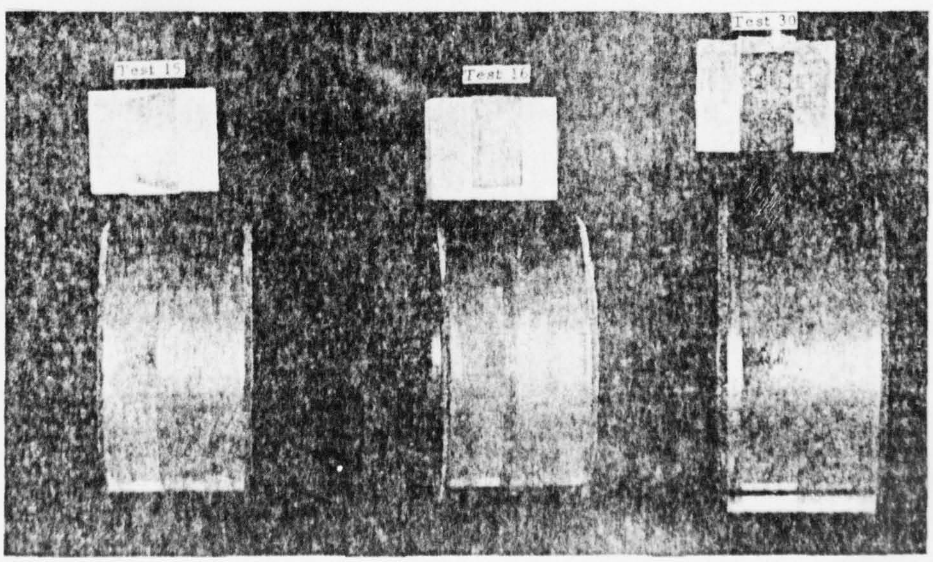


FIGURE 20. ALUMINUM BLOCKS AND TRIBALOY 800 COATED STEEL RINGS AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TESTS

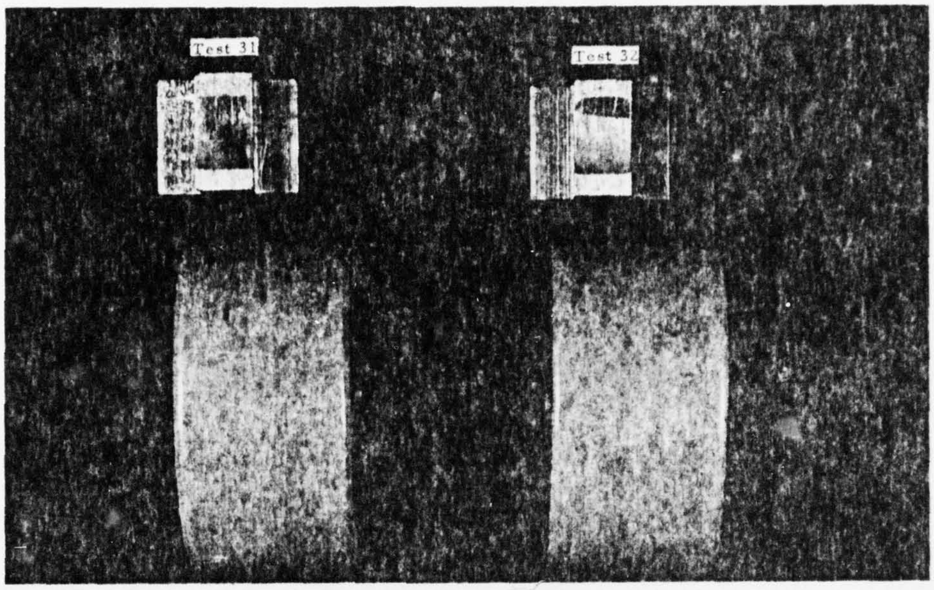


FIGURE 21. BRONZE BLOCKS AND NYLON 11 COATED STEEL RINGS AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TESTS

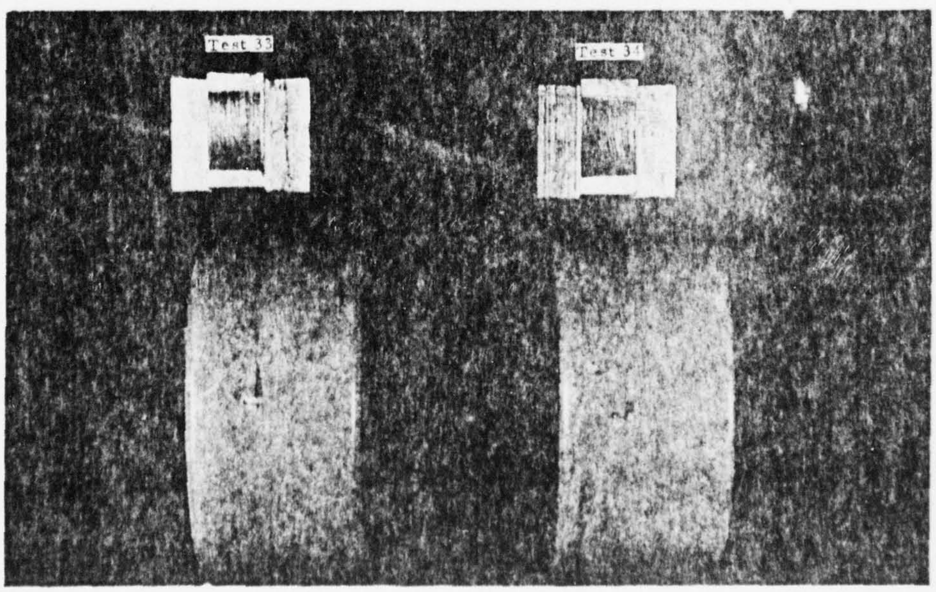
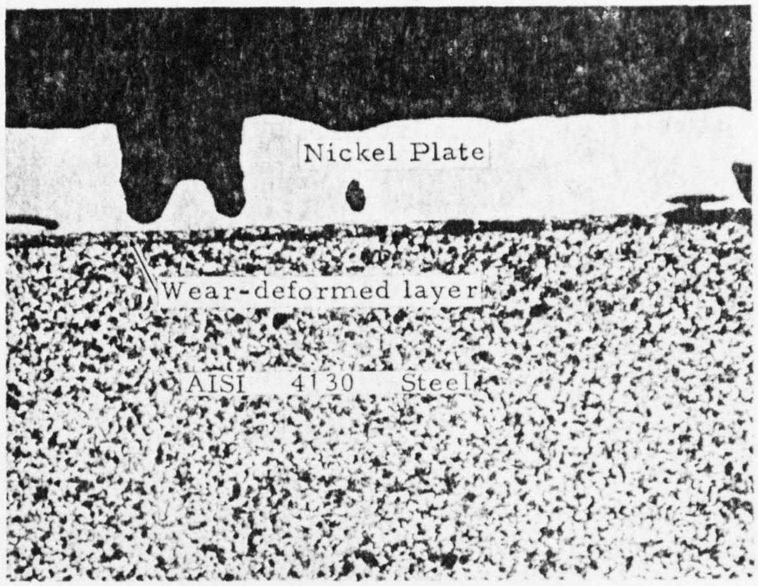
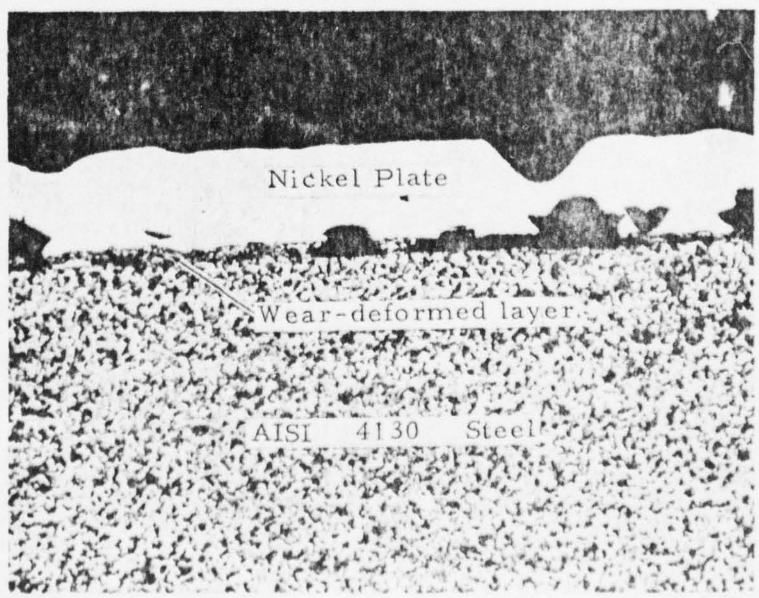


FIGURE 22. ALUMINUM BLOCKS AND NYLON 11 COATED STEEL RINGS AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TESTS



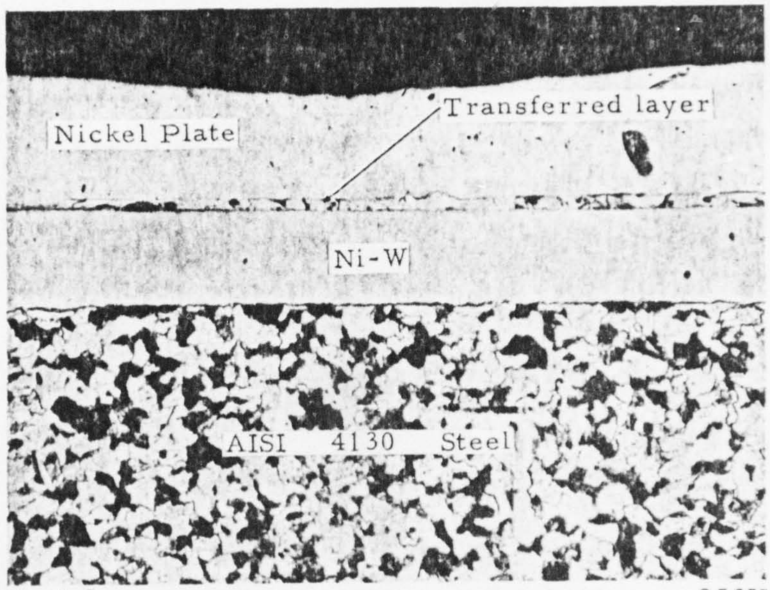
Test 3 75X

FIGURE 23. PHOTOMICROGRAPH OF UNCOATED STEEL RING AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TEST



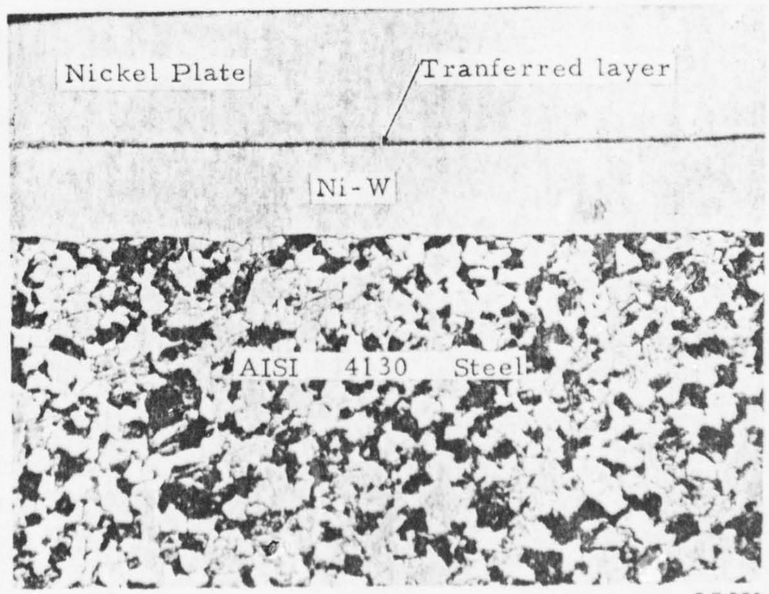
Test 1 75X

FIGURE 24. PHOTOMICROGRAPH OF UNCOATED STEEL RING AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TEST



Test 9 250X

FIGURE 25. PHOTOMICROGRAPH OF SELECTRON Ni-W COATED STEEL RING AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TEST

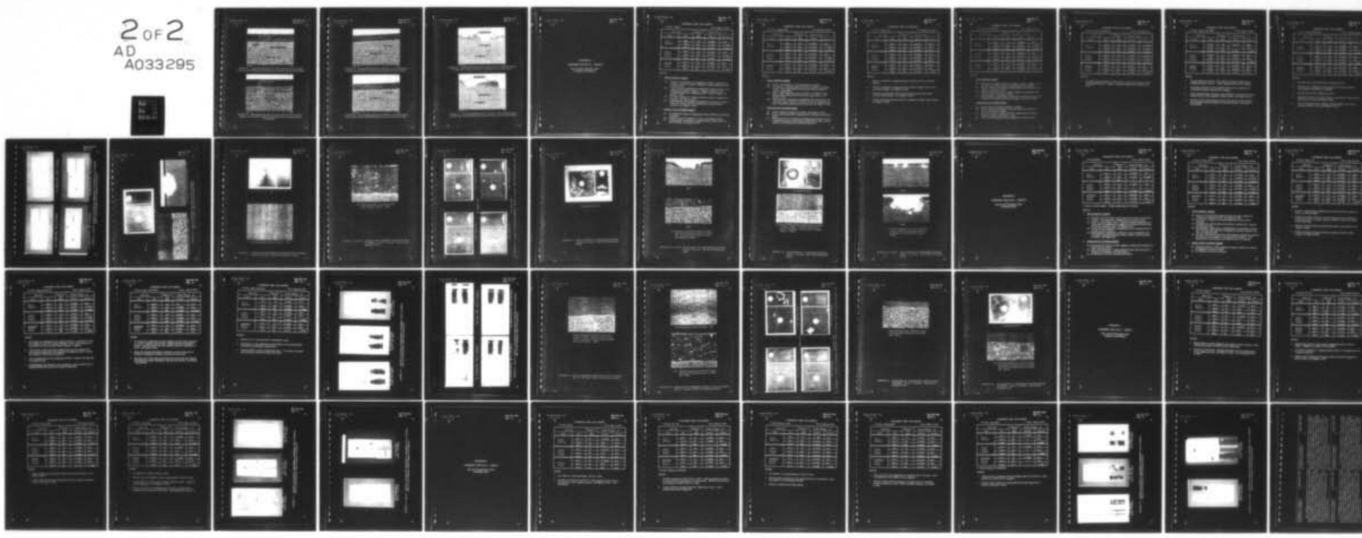


Test 13 250X

FIGURE 26. PHOTOMICROGRAPH OF SELECTRON Ni-W COATED STEEL RING AFTER SIMULATED ARRESTING GEAR WEAR TEST

AD-A033 295 SOUTHWEST RESEARCH INST SAN ANTONIO TEX F/G 11/3
EVALUATION OF COATINGS FOR AIR/FLUID ACCUMULATORS. (U)
SEP 76 R D BROWN, H C BURGHARD N00156-74-C-1660
UNCLASSIFIED SWRI-RS-634 NAEC-ENG-7884 NL

2 OF 2
AD
A033295



END
DATE
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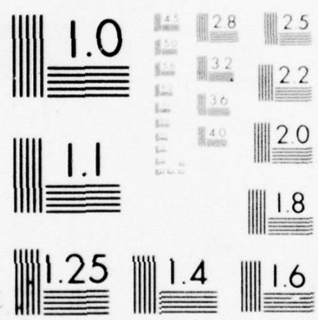
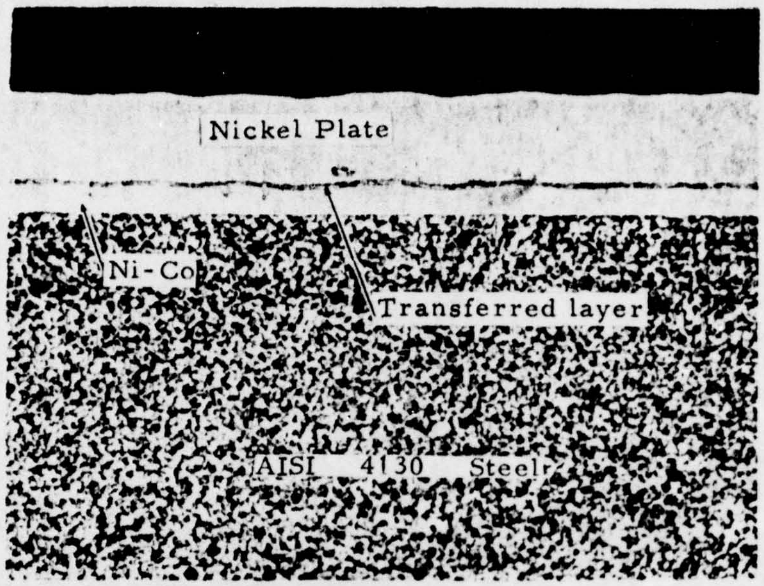
2-77

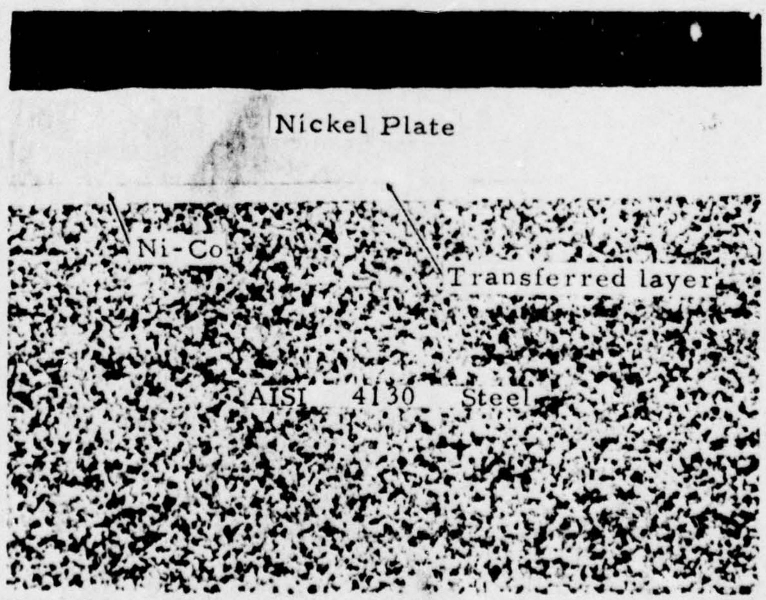


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A



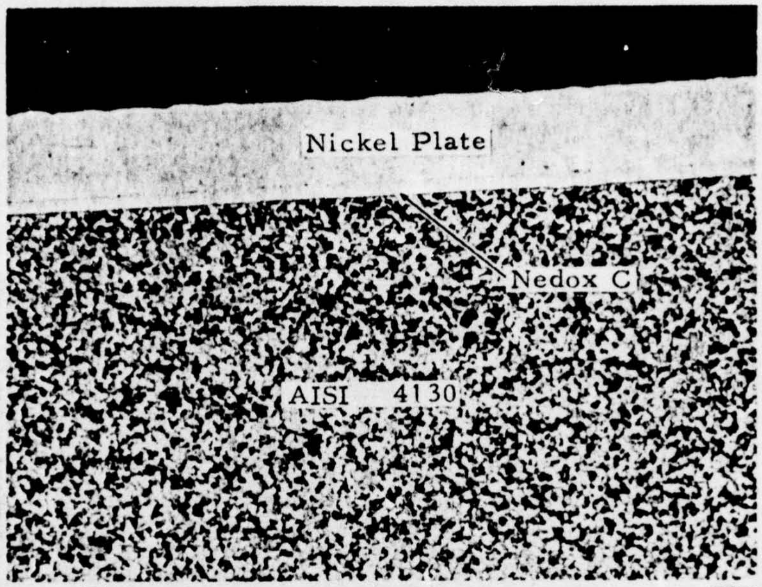
Test 22 75X

FIGURE 27. PHOTOMICROGRAPH OF SELECTRON Ni-Co COATED STEEL AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TEST



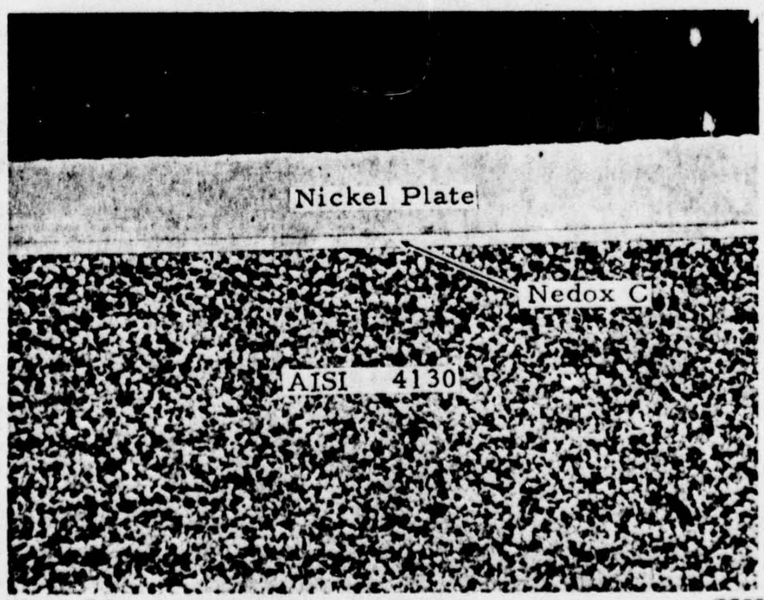
Test 26 75X

FIGURE 28. PHOTOMICROGRAPH OF SELECTRON Ni-Co COATED STEEL AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TEST



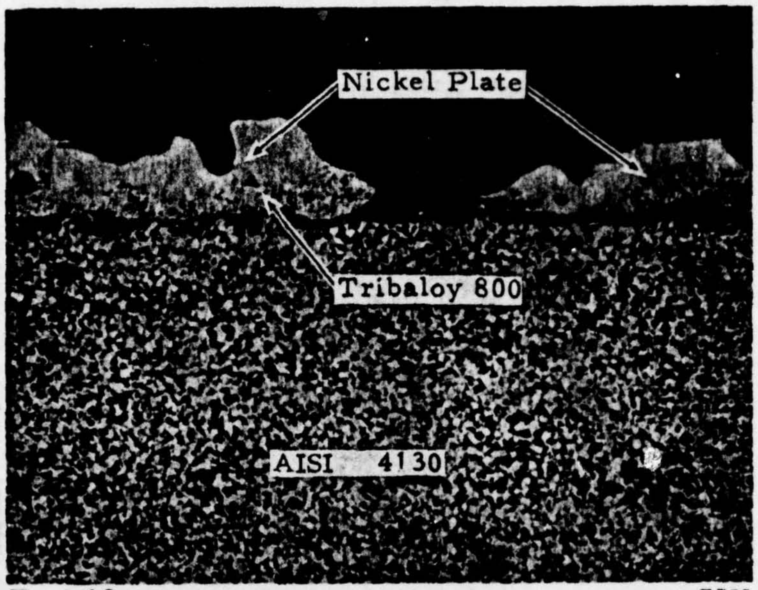
Test 24 75X

FIGURE 29. PHOTOMICROGRAPH OF NEDOX C COATED STEEL AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TEST



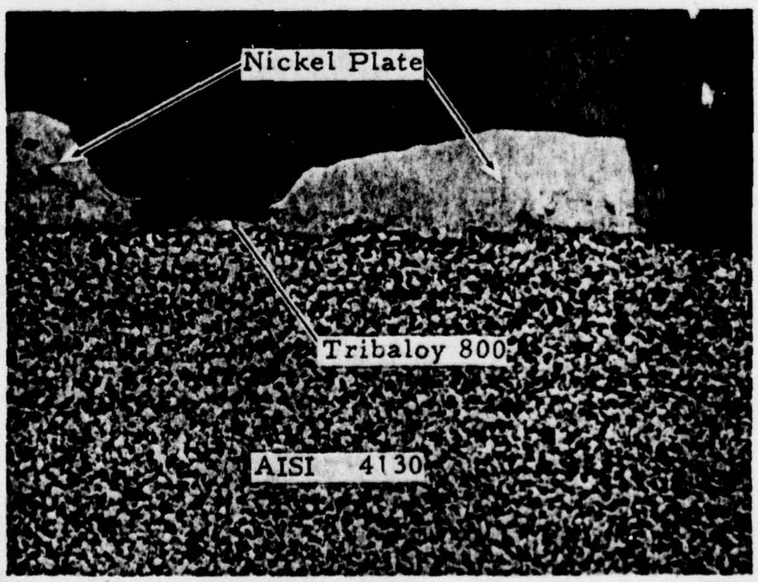
Test 28 75X

FIGURE 30. PHOTOMICROGRAPH OF NEDOX C COATED STEEL AFTER SIMULATED ARRESTING GEAR CATAPULT WEAR TEST



Test 18 75X

FIGURE 31. PHOTOMICROGRAPH OF TRIBALOY 800 COATED STEEL AFTER SIMULATED CATAPULT ACCUMULATOR WEAR TEST



Test 16 75X

FIGURE 32. PHOTOMICROGRAPH OF TRIBALOY 800 COATED STEEL AFTER SIMULATED ARRESTING GEAR ACCUMULATOR WEAR TEST

APPENDIX A

CORROSION TEST DATA - PHASE II

MIL-H-22072 Hydraulic Fluid
(Catapult Accumulator)

CORROSION TEST DATA SHEET

Coating: Nedox | Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	4B-1	30	+0.0002	N/A
	4B-2	174	-0.0005	-0.0159
	4B-3	261	-0.0131	-0.0773
Coated Crevice Coupon	4B-1	30	+0.0013	N/A
	4B-2	174	+0.0015	-0.0114
	4B-3	261	-0.0058	-0.0409
Bronze Crevice Coupon	4B-1	30	-0.0083	N/A
	4B-2	174	-0.1150	N/A
	4B-3	261	-0.1743	-0.2407

NOTES:

1. <u>Direct exposure coupons</u>.

   (a) Evidence of peeling of TFE observed on Series 1 and Series 2 coupons. Series 2 coupons exhibited a mottled appearance due to loss of TFE.

   (b) Visual and low magnification examination indicated loss of TFE coating from Series 3 coupons. Coupons exhibited a dull, roughened appearance suggesting mild corrosive attack, see Figure A-1(c).

   (c) No visual evidence of corrosive attack of Series 3 coupon after cleaning, see Figure A-2(a).

   (d) Metallographic examination established that coating on Series 3 coupon was intact and that no significant corrosive attack occurred, see Figure A-2(b).

2. <u>Coated crevice corrosion coupon</u>.

   (a) No significant change in appearance noted in Series 1 and Series 2 coupons.

   (b) Pitting occurred at bottom of crevice, see Figure A-2(a).

   (c) Metallographic examination revealed pitting of base metal beneath coating, see Figure A-2(c).

CORROSION TEST DATA SHEET

Coating: Tribaloy 800   Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	5B-1	36	+0.0080	N/A
	5B-2	181	-0.0189	-0.0729
	5B-3	236	+0.0375	-0.1428
Coated Crevice Coupon	5B-1	36	+0.0166	N/A
	5B-2	181	+0.0012	-0.0443
	5B-3	237	+0.0291	-0.1585
Bronze Crevice Coupon	5B-1	36	-0.0036	N/A
	5B-2	181	-0.1778	N/A
	5B-3	237	-0.2122	-0.2756

NOTES:

1. Direct exposure coupons.

   (a) Series 1 and Series 2, no visual evidence of attack.
   (b) No evidence of general attack of Series 3 coupon, see Figure A-1(d). Some edge attack and one peeled spot attributed to defect in application.
   (c) Clean, shiny appearance after cleaning, see Figure A-3(a). Intergranular network observed at low magnification, see Figure A-3(b).
   (d) Metallographic examination established that intergranular network was surface effect (no evidence of cracks in plating) and that no significant general attack occurred, see Figure A-3(c).

2. Coated crevice corrosion coupon.

   (a) Surface deposit at bottom of crevice, see Figure A-1(d).
   (b) Clean, matte finish after cleaning with no evidence of corrosive attack.
   (c) Blistering observed at bottom of coupon but attributed to defect in application since similar defects noted before tests, and no evidence of corrosion was observed at blisters.

CORROSION TEST DATA SHEET

Coating: Nylon 11A

Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	6B-1	26	+0.0621	N/A
	6B-2	186	+0.0538	N/A
	6B-3	274	+0.0395	N/A
Coated Crevice Coupon	6B-1	26	+0.0285	N/A
	6B-2	186	+0.0389	N/A
	6B-3	274	+0.0725	N/A
Bronze Crevice Coupon	6B-1	26	-0.0192	N/A
	6B-2	186	-0.1360	N/A
	6B-3	274	-0.1953	-0.2471

NOTES:

1. Series 1 and Series 2 coupons showed no visual evidence of coating damage.

2. Blisters developed in coating of Series 3 direct exposure and crevice corrosion coupons, see Figure A-4(a).

3. Blisters contained fluid when opened and some base metal attack occurred under blisters, see Figure A-4(a).

4. Similar blistering occured in Series 3 coupons for Nylon 11(B) coating, see Figure A-4(b).

CORROSION TEST DATA SHEET

Coating: Selectron Ni-W | Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	8B-1	22	-0.0026	N/A
	8B-2	166	-0.0061	-0.0355
	8B-3	253	+0.9695	-1.5097
Coated Crevice Coupon	8B-1	22	-0.0019	N/A
	8B-2	166	+0.0245	-0.0947
	8B-3	253	-0.1414	-0.6096
Bronze Crevice Coupon	8B-1	22	-0.0026	N/A
	8B-2	166	-0.1094	N/A
	8B-3	253	-0.1518	-0.2621

NOTES:

1. <u>Direct exposure coupon.</u>

   (a) Small pits developed in Series 1 coupon. Series 2 coupon darker in color with visual evidence of general corrosive attack.

   (b) Severe uniform corrosion and scale buildup occurred in Series 3 coupon, see Figure A-1(f).

   (c) Loss of plating on Series 3 coupon evident on visual inspection after cleaning, see Figure A-5(a).

   (d) Metallographic examination verified loss of plating and corrosion of substrate material on Series 3 coupon, see Figure A-5(b).

2. <u>Coated crevice corrosion coupon.</u>

   (a) Little evidence of attack in Series 1 coupon.

   (b) Severe pitting and buildup of corrosion product at bottom of crevice in Series 2 coupon.

   (c) Severe overall corrosion of Series 3 coupon similar to direct exposure coupon, see Figure A-1(f).

   (d) Loss of coating apparent after cleaning, see Figure A-5(a).

CORROSION TEST DATA SHEET

Coating: Selectron Ni-Co Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	9B-1	22	-0.0035	-0.0100
	9B-2	166	-0.0029	-0.1026
	9B-3	253	-0.0503	-0.3343
Coated Crevice Coupon	9B-1	22	-0.0014	-0.0061
	9B-2	166	-0.0065	-0.0176
	9B-3	253	-0.0513	-0.3590
Bronze Crevice Coupon	9B-1	22	-0.0028	N/A
	9B-2	166	-0.0988	N/A
	9B-3	253	-0.1608	-0.2304

NOTES:

1. Corrosive attack confined to tight crevice - only other attack at edges - maybe plating defect at edges. Coating satisfactory for exposed surfaces.

CORROSION TEST DATA SHEET

Coating: Bare 4130 (12B)

Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	12-B1	26	-0.0152	N/A
	12-B1	186		N/A
	12-B1	273	+.9193	-1.4381
Coated Crevice Coupon	12-B1	26	-0.0027	N/A
	12-B1	186	+0.0512	N/A
	12-B1	273	+0.1562	-0.9668
Bronze Crevice Coupon	12-B1	26	-0.0223	N/A
	12-B1	186	-0.0895	N/A
	12-B1	273	-0.1895	N/A

NOTES:

1. General blued film with few very small rust spots (evident at low magnification) for Series 1. Direct exposure and crevice coupons.

2. Rust spots on Series 2 direct exposure and crevice coupons more numerous and larger than Series 1 coupons.

3. Severe general attack and heavy scale buildup occurred on both direct exposure and crevice coupons in Series 3 tests, see Figure A-1(b).

4. Specimen 12B-1 was used for all three test series and was weighed and examined (without cleaning) at end of the Series 1 and Series 2 test periods.

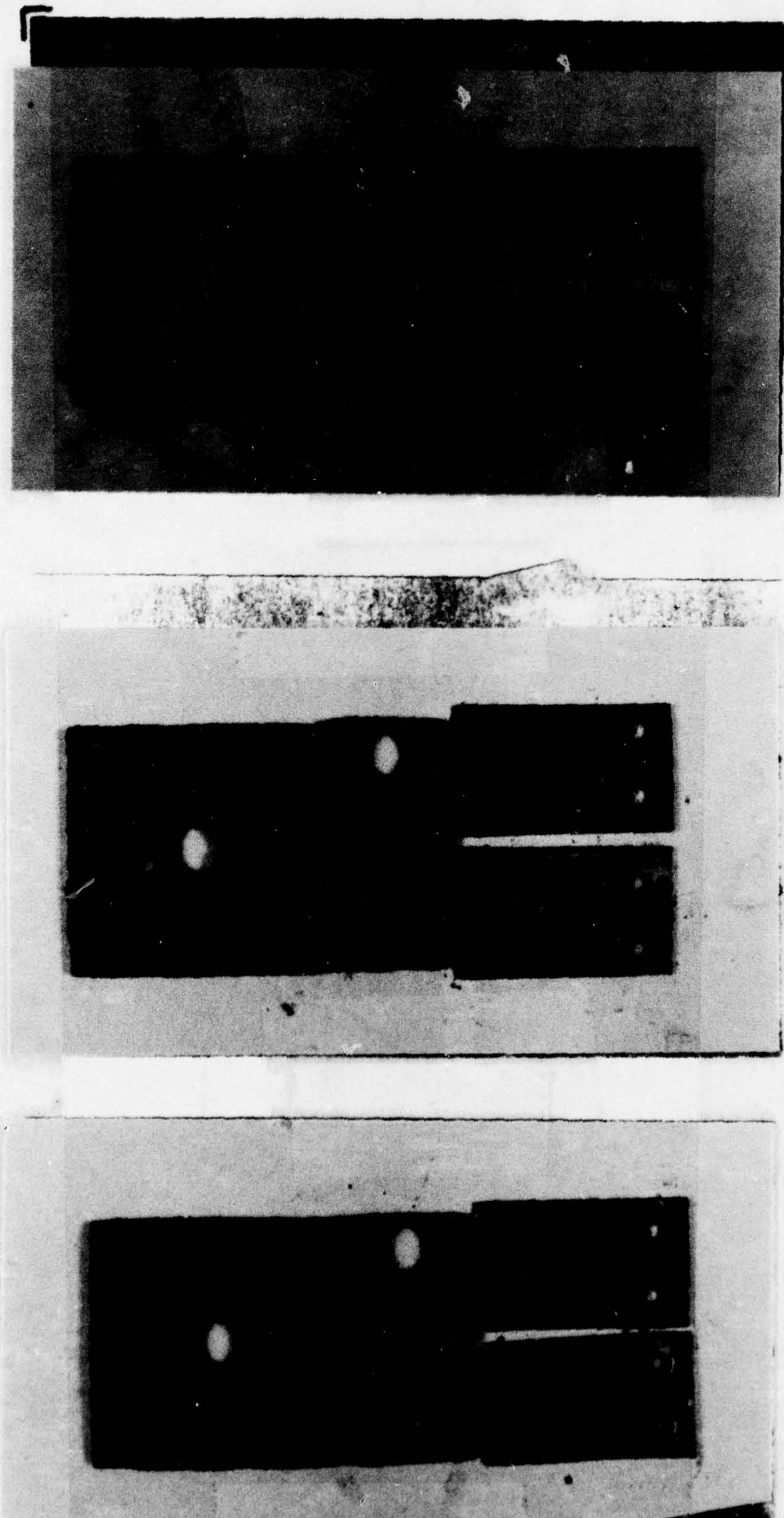
CORROSION TEST DATA SHEET

Coating: Bare 4130 (1B) Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	1B-1	26	-0.0020	N/A
	1B-1	186	+0.0492	N/A
	1B-3	273	+1.0115	-1.7551
Coated Crevice Coupon	1B-1	26	-0.0014	N/A
	1B-1	186	+0.0212	N/A
	1B-3	273	-0.3168	-0.9536
Bronze Crevice Coupon	1B-1	26	-0.0216	N/A
	1B-1	186	-0.1102	N/A
	1B-3	273	-0.1582	-0.2054

NOTES:

1. Specimen 1B-1 used for Series 1 and Series 2 tests.
2. Specimen 1B-3 exposed for entire Series 3 test period without intermediate examination or weighing.
3. Results very similar to Specimen 12B-1.
4. Blued film and few rust spots in Series 1 and Series 2 tests on direct exposure and crevice corrosion coupon.
5. Severe rusting and scale buildup on direct exposure and crevice coupons in Series 3 test, see Figure A-1(a).

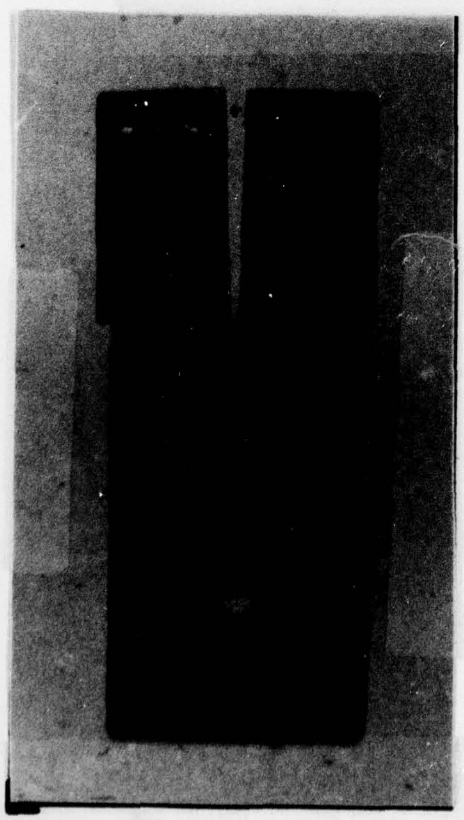


(a) Bare 4130 steel.
(1B-3, 273 days).

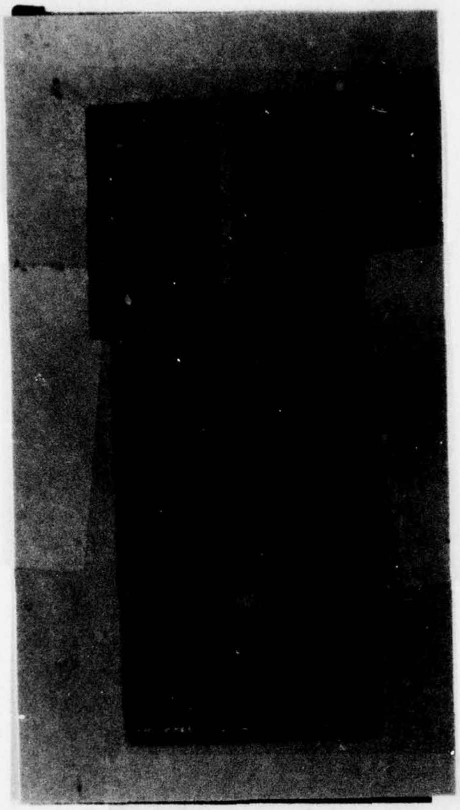
(b) Bare 4130 steel.
(12B-1, 273 days).

(c) Nedox.
(4B-3, 261 days).

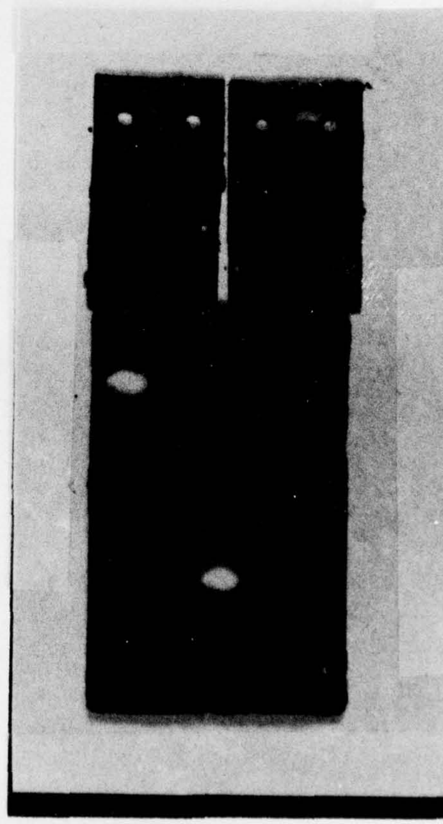
FIGURE A-1. SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS.
MIL-H-22072 Hydraulic Fluid (Catapult Accumulator).



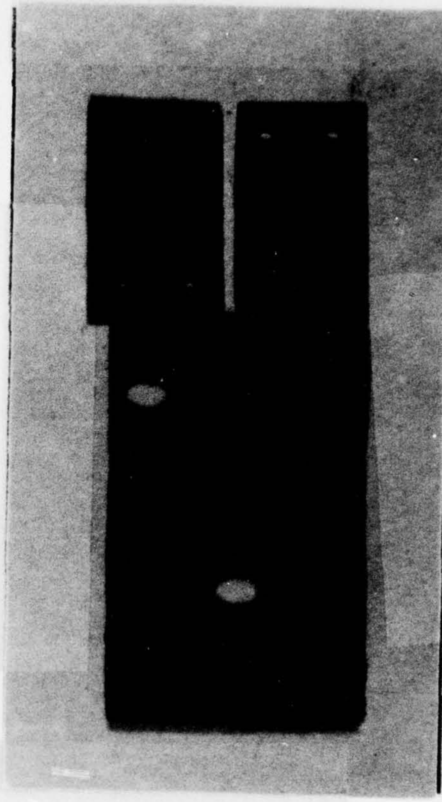
(d) Tribaloy 800. (5B-3, 236 days).



(e) Nylon 11(B). (6B-3, 274 days).

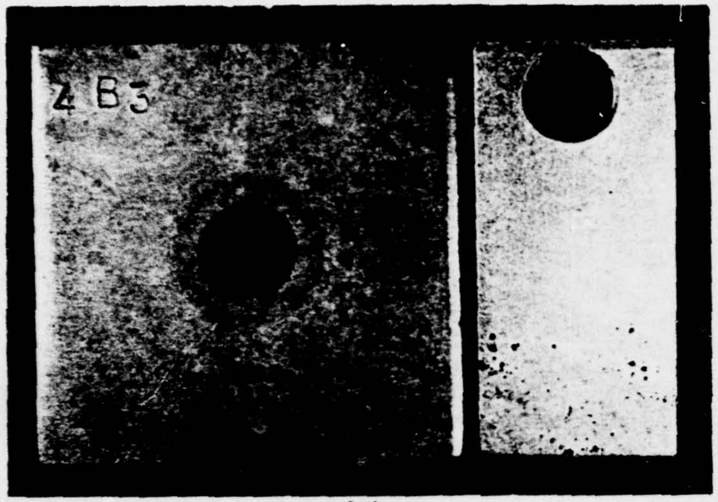


(f) Selectron Ni-W. (8B-3, 253 days).



(g) Selectron Ni-Co. (9B-3, 253 days).

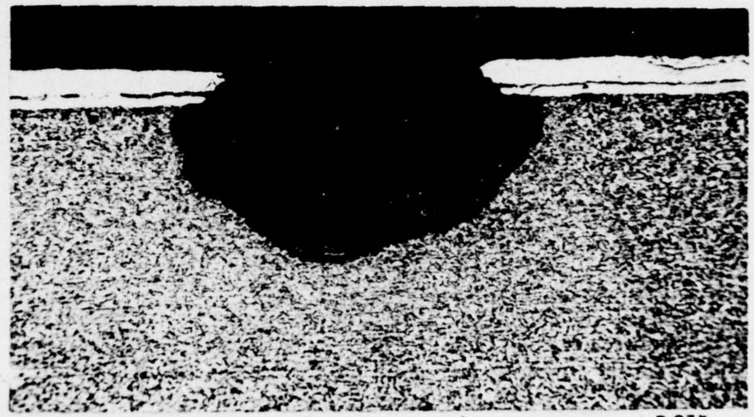
FIGURE A-1 (cont'd). SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS.
MIL-H-22072 Hydraulic Fluid (Catapult Accumulator).



(a)

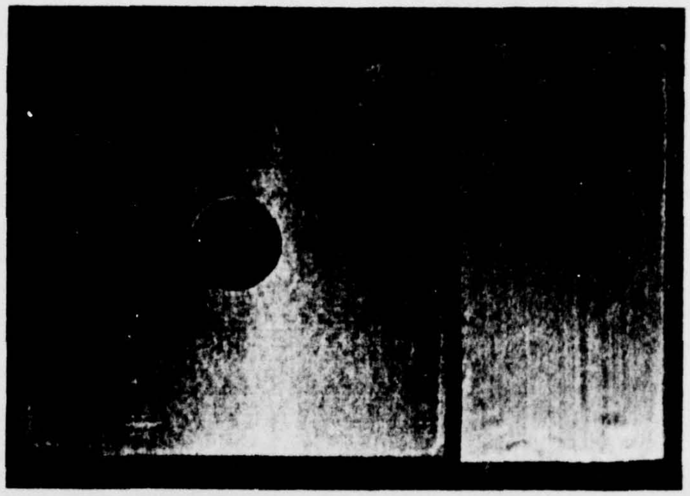
7A-2

(b) Direct exposure coupon. 1000X.

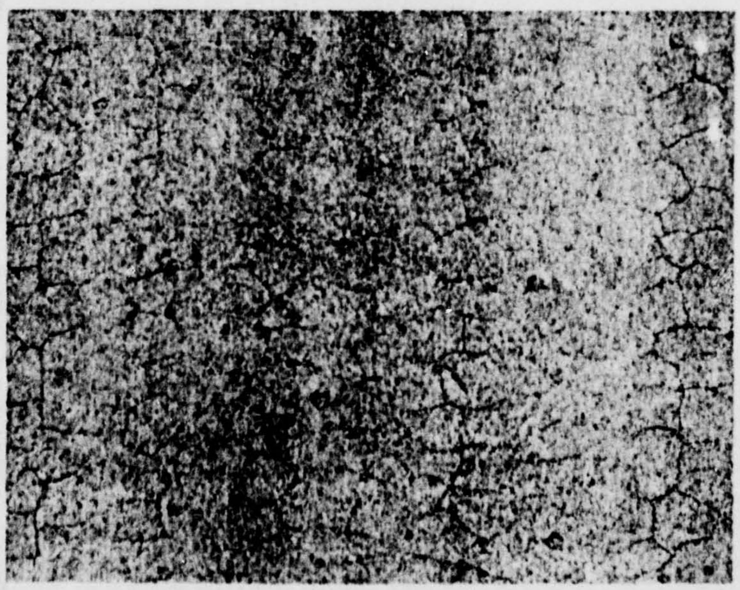


(c) Pits in crevice corrosion coupon. 50X.

FIGURE A-2. NEDOX CORROSION COUPONS AFTER CLEANING.
Series 3, 261 days. MIL-H-22072 Hydraulic Fluid.

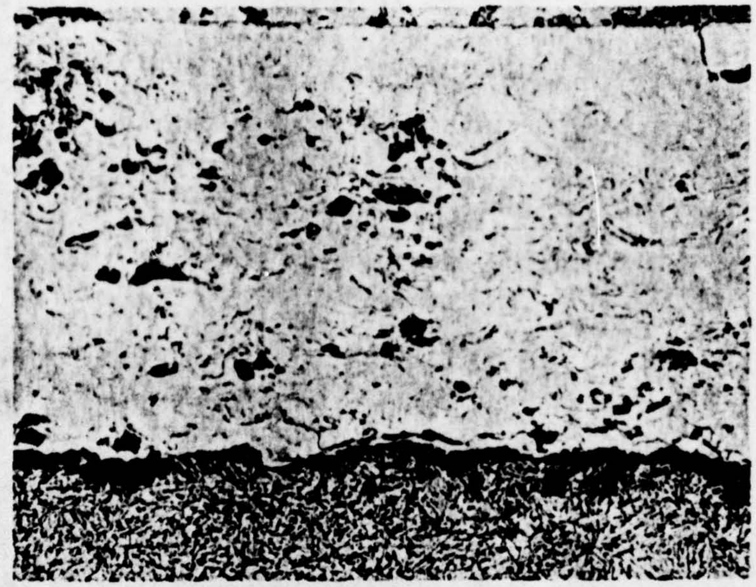


(a)



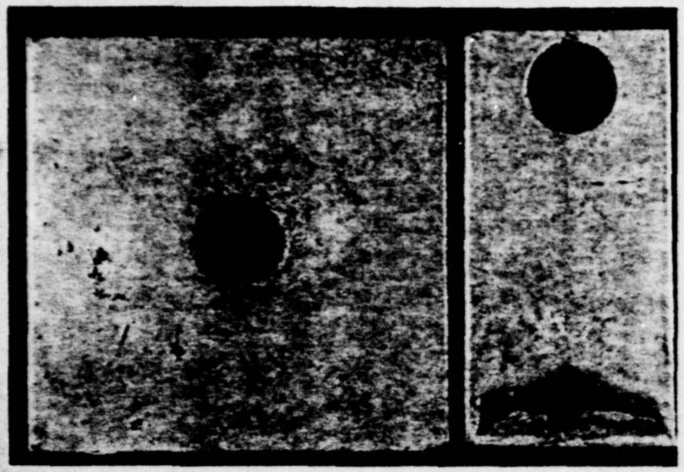
(b) Intergranular surface network. 10X.

FIGURE A-3. TRIBALOY 800 CORROSION COUPONS AFTER CLEANING. Series 3, 236 days. MIL-H-2202 Hydraulic Fluid.

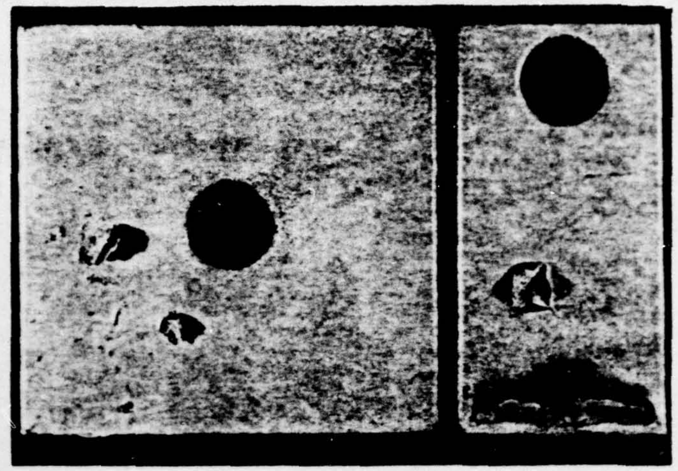


(c) Photomicrograph of section through direct exposure coupon. 300X.

FIGURE A-3 (cont'd). TRIBALOY 800 CORROSION COUPONS AFTER CLEANING. Series 3, 236 days. MIL-H-2202 Hydraulic Fluid.

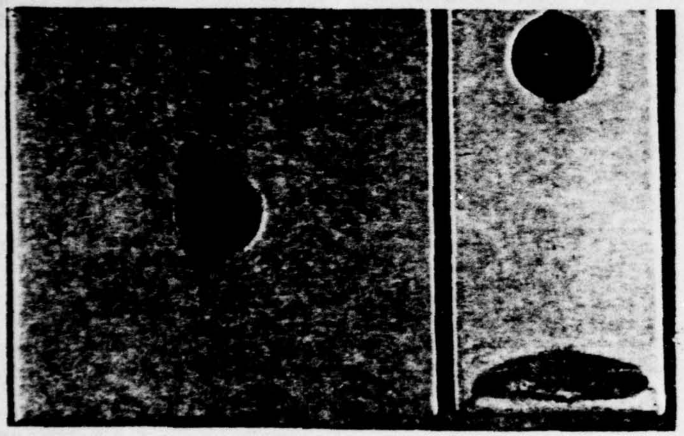


6B-3, After test.

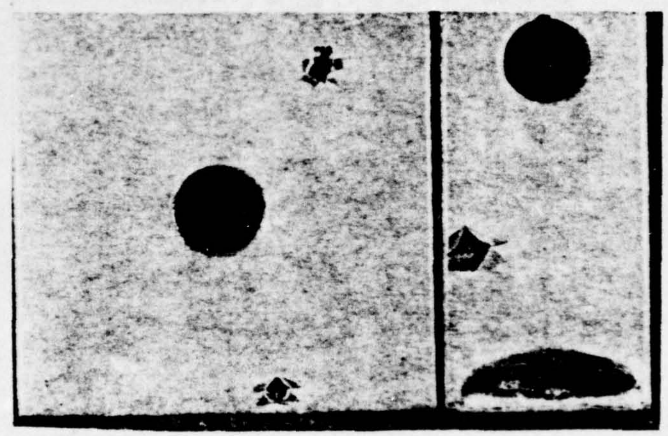


6B-3, Blisters opened.

(a) Nylon 11(A).



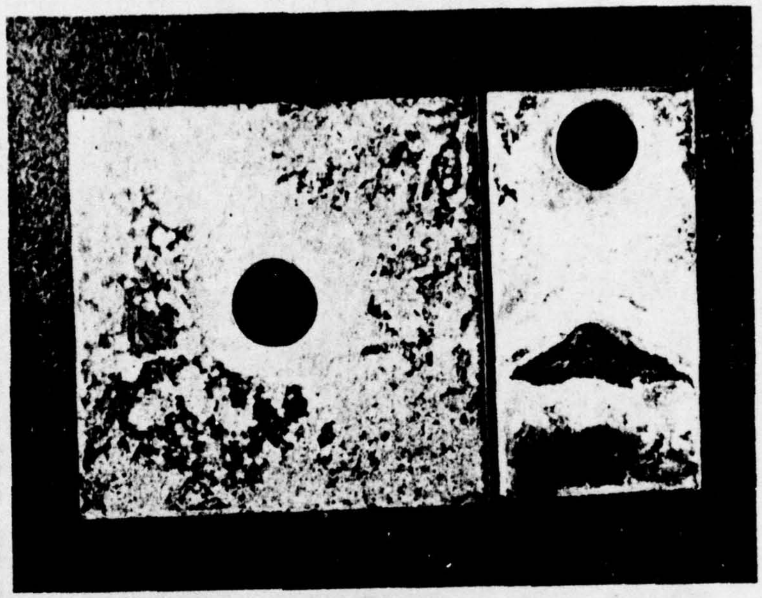
7B-3, After test.



7B-3, Blisters opened.

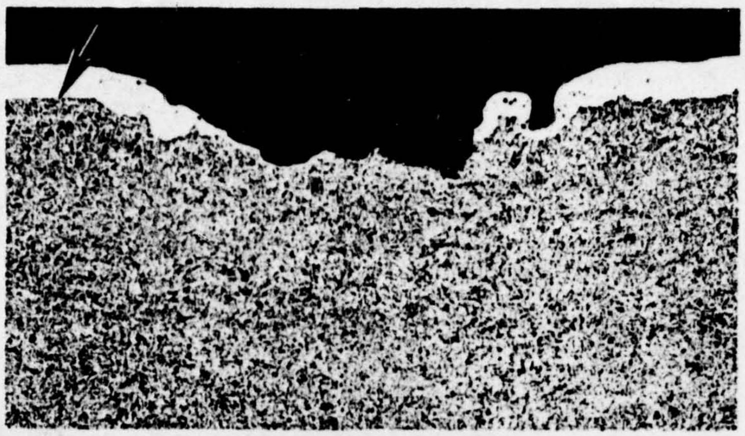
(b) Nylon 11(B).

FIGURE A-4. NYLON 11 CORROSION COUPONS. Series 3, 274 days. MIL-H-22072 Hydraulic Fluid.

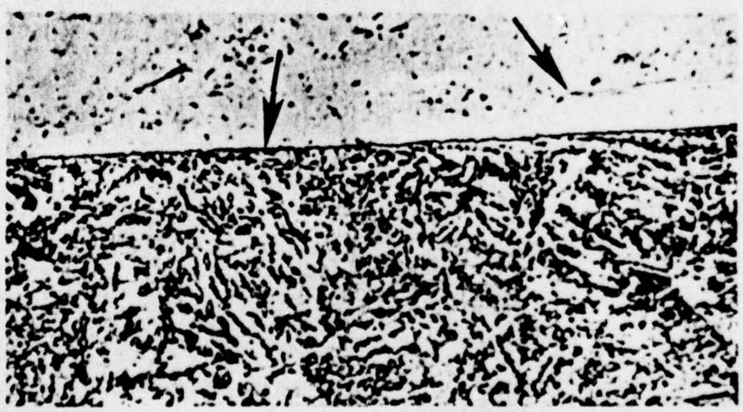


(a) Specimen 8B-3.

FIGURE A-5. SELECTRON Ni-W CORROSION SPECIMENS. Series 3, 253 days. MIL-H-22072 Hydraulic Fluid.



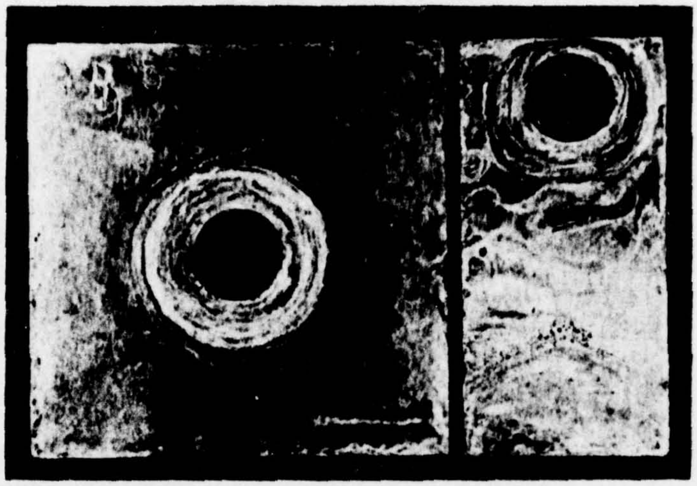
100X



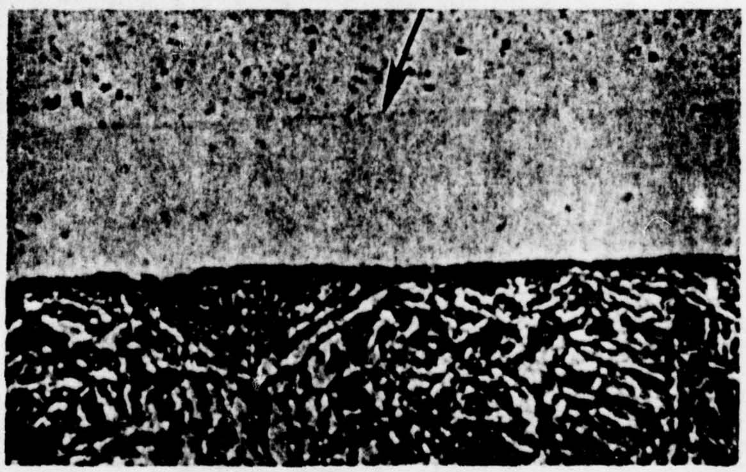
1000X

(b) Section through direct exposure coupon. Specimen nickel plated prior to sectioning. Arrows indicate original surface and remnant of coating.

FIGURE A-5. (cont'd). SELECTRON Ni-W CORROSION SPECIMENS. Series 3, 253 days. MIL-H-22072 Hydraulic Fluid.

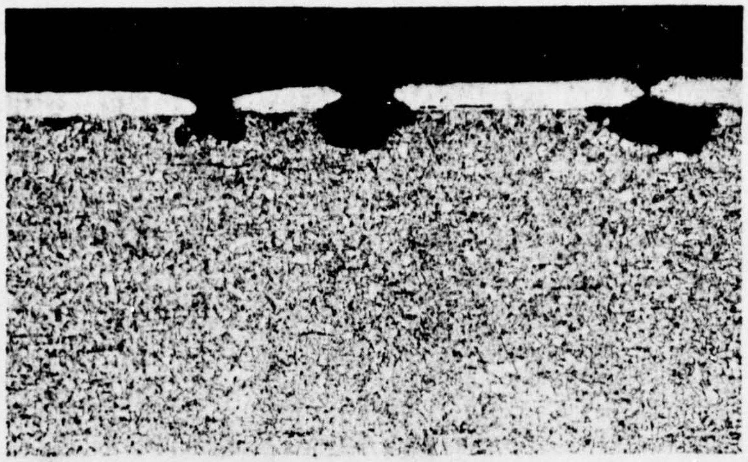


(a) Specimen 9B-3.

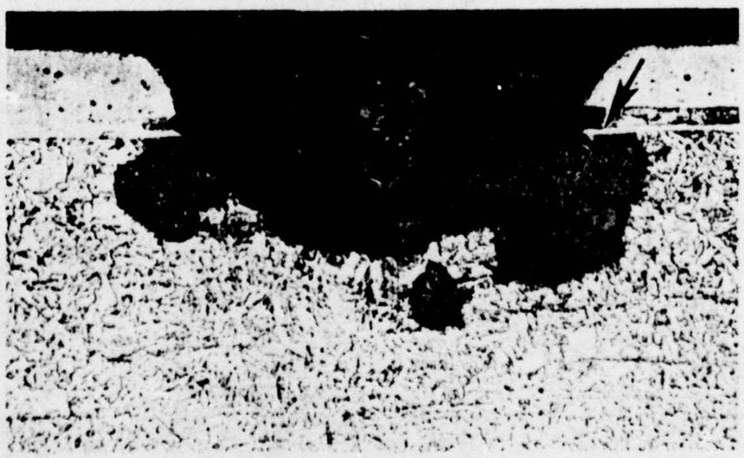


(b) Section through intact coating zone on crevice corrosion coupon. Specimen nickel plated prior to sectioning. Arrow indicates coating surface. 1000X.

FIGURE A-6. SELECTRON Ni-Co CORROSION COUPONS. Series 3, 253 days. MIL-H-22072 Hydraulic Fluid.



100X



300X

(c) Section through pits in crevice corrosion coupon. Specimen nickel plated prior to sectioning. Arrow indicates original coating.

FIGURE A-6. (cont'd). SELECTRON Ni-Co CORROSION COUPONS. Series 3, 253 days. MIL-H-22072 Hydraulic Fluid.

APPENDIX B

CORROSION TEST DATA - PHASE II

**MIL-H-5559 Hydraulic Fluid
(Arresting Gear)**

CORROSION TEST DATA SHEET

Coating: Nedox　　　　Fluid: MIL-H-5559

Specimen Type	Specimen No.	Exposure Time days	Weight Change - gm Rinsed	Weight Change - gm Cleaned
Direct Exposure	4A-1	30	+0.0003	N/A
	4A-2	174	-0.0231	-0.0445
	4A-3	261	*	*
Coated Crevice Coupon	4A-1	30	-0.0304	N/A
	4A-2	174	*	*
	4A-3	261	-0.0069	-0.0189
Aluminum Crevice Coupon	4A-1	30	+0.0062	N/A
	4A-2	174	+0.0075	N/A
	4A-3	261	+0.0167	-0.0028

* Error in initial weight. Weight change data not obtained.

NOTES:

1. Direct exposure coupons.

   (a) Evidence of loss of TFE coating observed in Series 1 and Series 2 coupons. Dull appearance suggests mild corrosive attack.
   (b) Series 3 coupon darker color. General roughened appearance in visual and low magnification suggests more extensive attack than for shorter exposure time, see Figure B-1(c).
   (c) Visual and low magnification appearance after cleaning indicative of mild corrosive attack.
   (d) Metallographic examination of Series 3 coupon established that coating was generally sound and that no major corrosive attack occurred, see Figure B-2.

2. Coated crevice corrosion coupons.

   (a) All specimens similar to direct exposure coupons with evidence of mild corrosive attack.
   (b) After cleaning Series 3 coupon appeared clean and sound with no evidence of significant corrosive attack.
   (c) No evidence of crevice corrosion was noted.

CORROSION TEST DATA SHEET

Coating: Tribaloy 800 — Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	5A-1	36	+0.0683	N/A
	5A-2	181	+0.0874	-0.0215
	5A-3	236	+0.1246	+0.0034
Coated Crevice Coupon	5A-1	36	+0.0326	N/A
	5A-2	181	+0.0357	-0.0253
	5A-3	267	+0.0632	-0.0232
Aluminum Crevice Coupon	5A-1	36	+0.0091	N/A
	5A-2	181	+0.0077	N/A
	5A-3	267	+0.0182	-0.0024

NOTES:

1. Direct exposure coupons.

(a) After test all specimens appeared clean and shiny without any evidence of corrosive attack, see Figure B-1(d).
(b) No evidence of general corrosive attack was observed after cleaning.
(c) Intergranular network observed on Series 2 and Series 3 coupons, see Figure B-3(a).
(d) Metallographic examination established that intergranular network was a surface effect and that no significant attack of coating occurred, see Figure B-3(b).
(e) One spot with definite separation and bulging of plating was observed but there was no evidence of corrosion at this location. This plating defect was present on the specimen prior to testing.

2. Coated crevice corrosion coupons

(a) Generally similar to direct exposure coupons without any evidence of significant corrosive attack.
(b) No evidence of crevice corrosion.

CORROSION TEST DATA SHEET

Coating: Nylon 11A

Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	6A-1	29	+0.0327	N/A
	6A-2	189	+0.0602	N/A
	6A-3	276	+0.1167	N/A
Coated Crevice Coupon	6A-1	29	+0.0253	N/A
	6A-2	189	+0.0579	N/A
	6A-3	276	+0.1172	N/A
Aluminum Crevice Coupon	6A-1	29	-0.0050	N/A
	6A-2	189	+0.0093	N/A
	6A-3	276	+0.0146	+0.0035

NOTES:

1. Series 1 coupons (direct exposure and crevice) showed no visual evidence of coating damage.

2. Blisters developed in Series 2 crevice coupon and in both direct exposure and crevice corrosion coupons in Series 3 tests, see Figure B-1(e) and B-4(a).

3. Blisters contained fluid when opened and surface under blisters was rough but clean.

4. Similar blistering occurred in Series 3 coupons for Nylon 11(B) coating, see Figure B-4(b).

CORROSION TEST DATA SHEET

Coating: Selectron Ni-W

Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	8A-1	22	-0.0089	N/A
	8A-2	166	-0.0098	-0.0548
	8A-3	253	-0.0433	-0.0866
Coated Crevice Coupon	8A-1	22	-0.0013	N/A
	8A-2	166	-0.0057	-0.0318
	8A-3	253	-0.0182	-0.0493
Aluminum Crevice Coupon	8A-1	22	+0.0070	N/A
	8A-2	166	+0.0134	N/A
	8A-3	253	+0.0086	+0.0030

NOTES:

1. <u>Direct exposure coupons.</u>

   (a) Tight dark film developed on Series 1 coupon but no visual evidence of corrosive attack.
   (b) Series 2 and Series 3 specimens show evidence of slight roughening of coating surface. Same tight hard, dark film as in Series 1 test, see Figure B-1(f).
   (c) Patches of mild attack (surface roughening) of Series 3 specimen evident at low magnification after cleaning.
   (d) Metallographic examination of Series 3 coupon established coating suffered moderate attack and small local penetrations developed see Figure B-5.

2. <u>Coated crevice corrosion coupons.</u>

   (a) Generally similar to direct exposure coupons.
   (b) Minor pitting occurred at base of crevice in Series 2 and Series 3 tests indicating possible susceptibility to crevice corrosion.

CORROSION TEST DATA SHEET

Coating: Selectron Ni-Co — Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	9A-1	22	-0.0398	N/A
	9A-2	166	-0.0877	-0.1101
	9A-3	253	-0.3619	-0.4000
Coated Crevice Coupon	9A-1	22	-0.0107	N/A
	9A-2	166	-0.0363	-0.0512
	9A-3	253	-0.0752	-0.1198
Aluminum Crevice Coupon	9A-1	22	+0.0048	N/A
	9A-2	166	+0.0085	N/A
	9A-3	253	+0.0146	+0.0031

NOTES:

1. Dark tight film developed on all coupons in Series 1 and Series 2 tests. No evidence of corrosive attack in Series 1 tests; some indication of local zones of mild corrosive attack in Series 2 coupons.

2. After Series 3 tests both direct exposive and crevice coupons exhibited mottled appearance with indication of significant loss of coating. No evidence of corrosion of substrate.

3. After cleaning severe loss of plating on Series 3 coupons was apparent, see Figure B-1(g).

4. Metallographic examination of direct exposure coupon verified loss of plating and absence of corrosive attack of substrate.

CORROSION TEST DATA SHEET

Coating: Bare 4130 (12A)

Fluid: MIL-H-5559

Specimen Type	Specimen No.	Exposure Time days	Weight Change - gm Rinsed	Weight Change - gm Cleaned
Direct Exposure	12A-1	34	0.0	N/A
	12A-1	195	-0.0035	N/A
	12A-1	281	-0.0043	-0.0129
Coated Crevice Coupon	12A-1	34	0.0008	N/A
	12A-1	195	-0.0043	N/A
	12A-1	281	-0.0099	-0.0173
Aluminum Crevice Coupon	12A-1	34	+0.0023	N/A
	12A-1	195	0.0054	N/A
	12A-1	281	0.0071	N/A

NOTES:

1. No evidence of significant corrosive attack of either direct exposure or crevice coupons in any of tests. Slight blued film developed in Series 1 test and similar film was present in Series 2 and Series 3 tests, see Figure B-1(b).

2. Slight discoloration developed at bottom of crevice coupon but no evidence of significant crevice corrosion was observed.

3. Specimen 12A-1 was used for all three test series and was weighed and examined (without cleaning) at the end of the Series 1 and Series 2 test periods.

CORROSION TEST DATA SHEET

Coating: Bare 4130 (1A) Fluid: MIL-H-5559

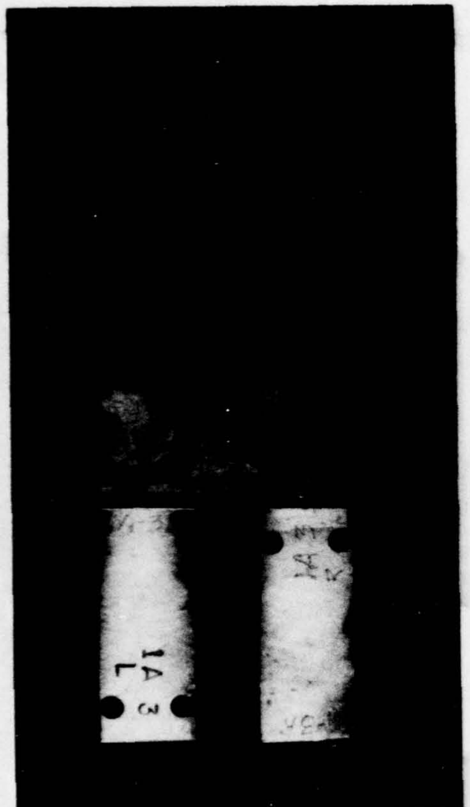
Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	1A-1	34	+0.0009	N/A
	1A-1	194	-0.0035	N/A
	1A-3	281	+0.0028	-0.0045
Coated Crevice Coupon	1A-1	34	-0.0004	N/A
	1A-1	197	+0.0032	N/A
	1A-3	281	+0.0026	-0.0033
Aluminum Crevice Coupon	1A-1	34	+0.0036	N/A
	1A-1	197	-0.0001	N/A
	1A-3	281	+0.0112	-0.0029

NOTES:

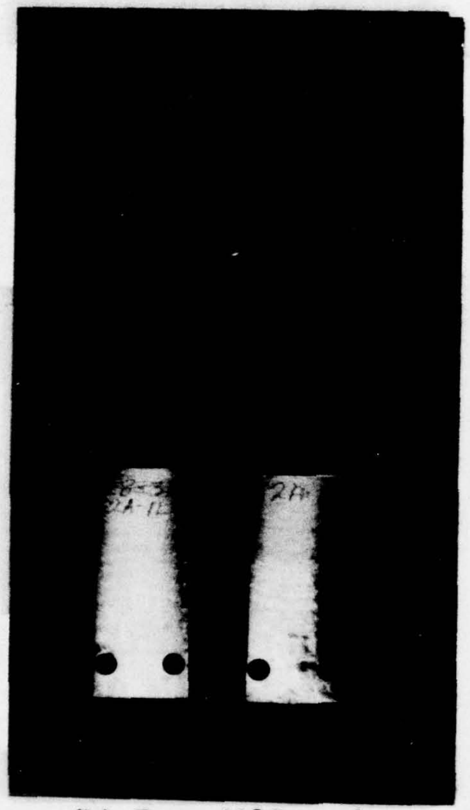
1. Specimen 1A-1 used for Series 1 and Series 2 tests.

2. Specimen 1A-3 was exposed for entire Series 3 test period without intermediate weighing or examination.

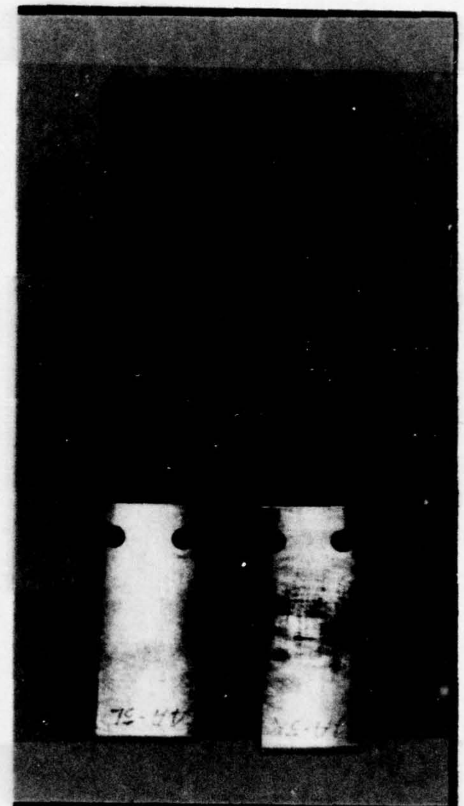
3. Results similar to tests on Specimen 12B-1. No evidence of significant attack was observed in any of the tests.



(a) Bare 4130 steel.
(1A-3, 281 days).

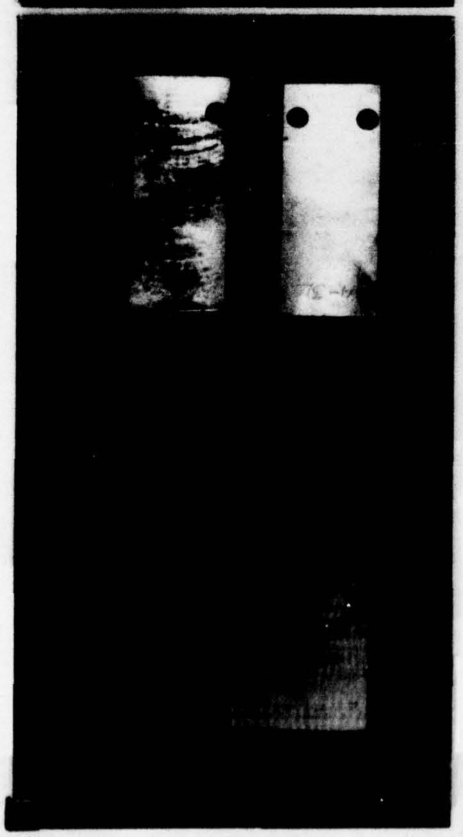


(b) Bare 4130 steel.
(12A-1, 281 days).

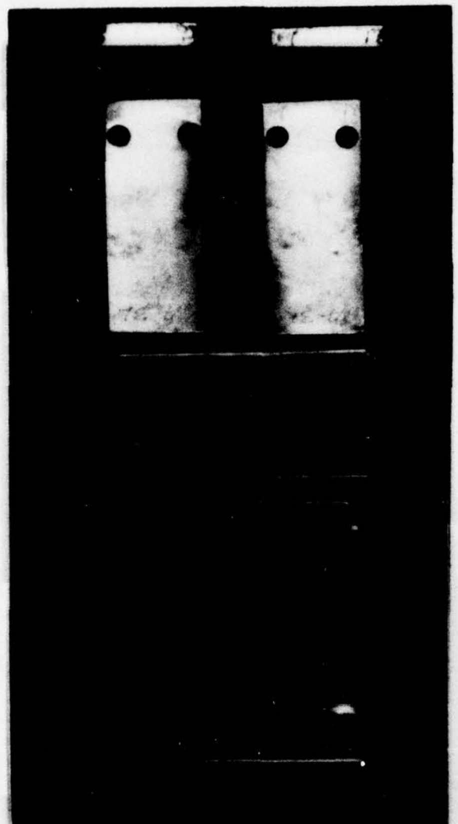


(c) Nedox.
(4A-3, 261 days).

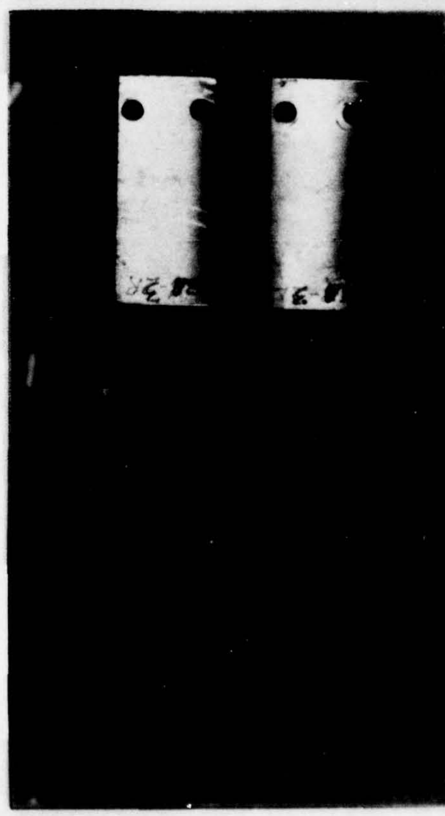
FIGURE B-1. SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS.
MIL-H-5559 Hydraulic Fluid (Arresting Gear).



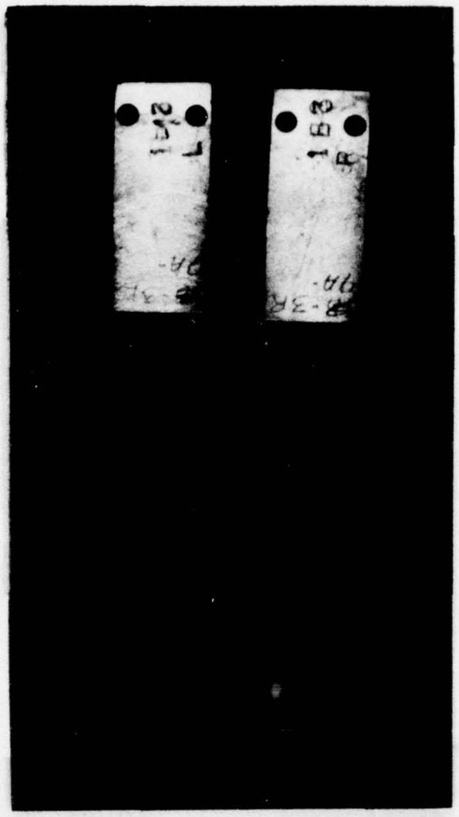
(d) Tribaloy 800. (5A-3, 236 days).



(e) Nylon 11(B). (6A-3, 276 days).

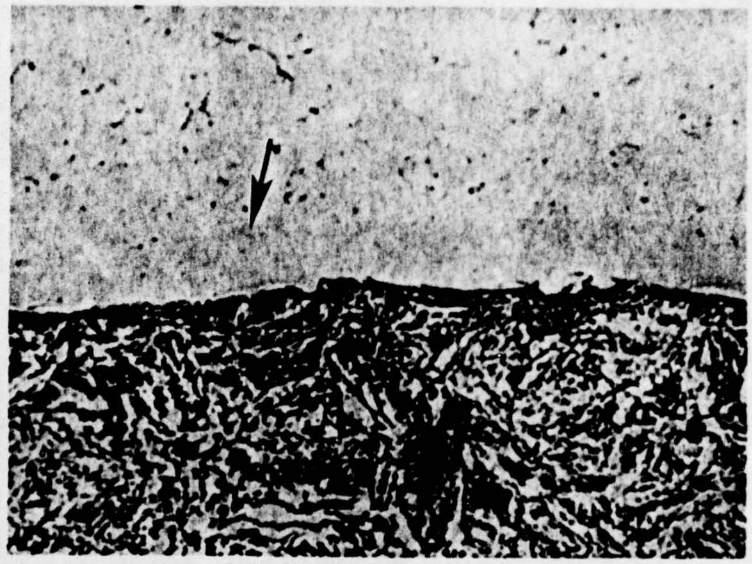


(f) Selectron Ni-W. (8A-3, 253 days).



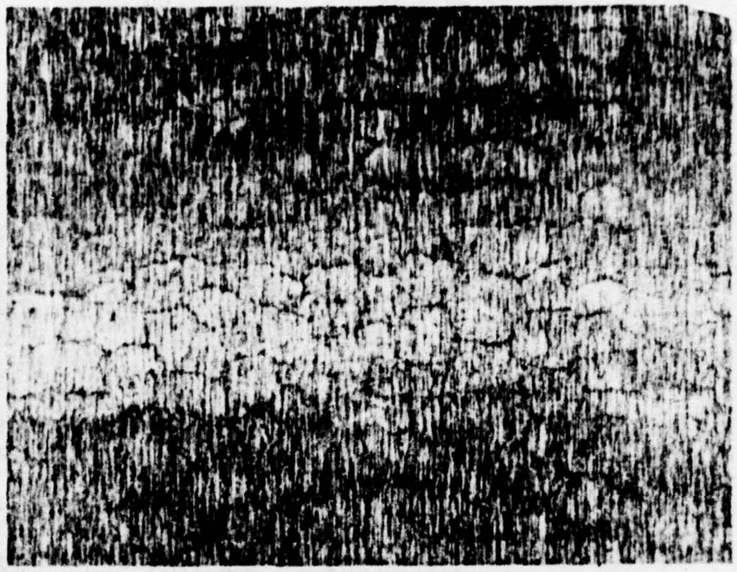
(g) Selectron Ni-Co. (9A-3, 253 days).

FIGURE B-1 (cont'd). SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS. MIL-H-5559 Hydraulic Fluid (Arresting Gear).



Photomicrograph of section through direct exposure coupon. Specimen nickel plated prior to sectioning. Arrow indicates outer surface of coating. 1000X.

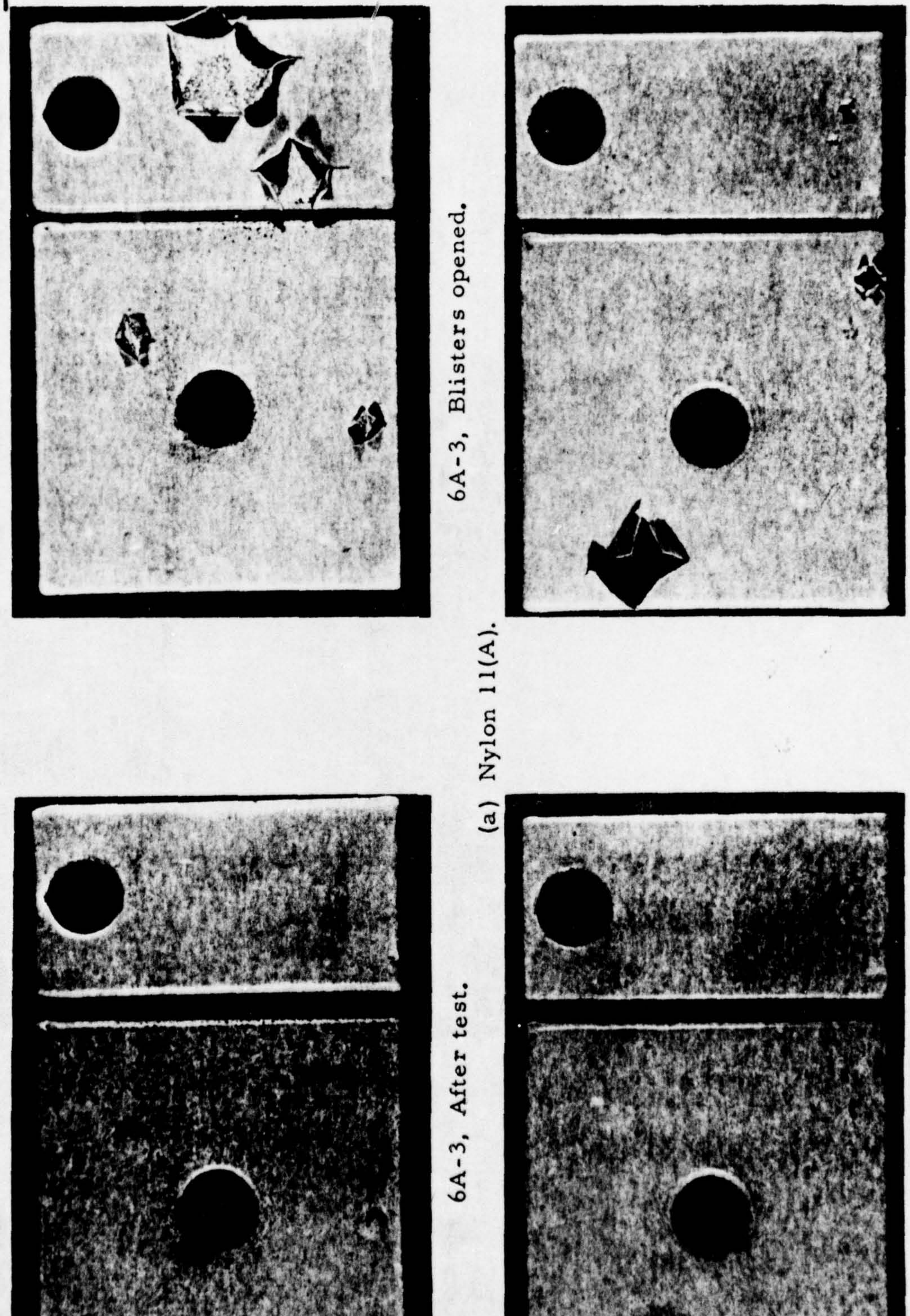
FIGURE B-2. NEDOX CORROSION SPECIMEN AFTER CLEANING. Series 3, 261 days. MIL-H-5559 Hydraulic Fluid.



(a) Intergranular surface network. 10X.

(b) Section through direct exposure coupon. Specimen nickel plated prior to sectioning. 300X.

FIGURE B-3. TRIBALOY 800 CORROSION COUPON AFTER CLEANING. Series 3, 267 days, MIL-H-5559 Hydraulic Fluid.



6A-3, After test.

6A-3, Blisters opened.

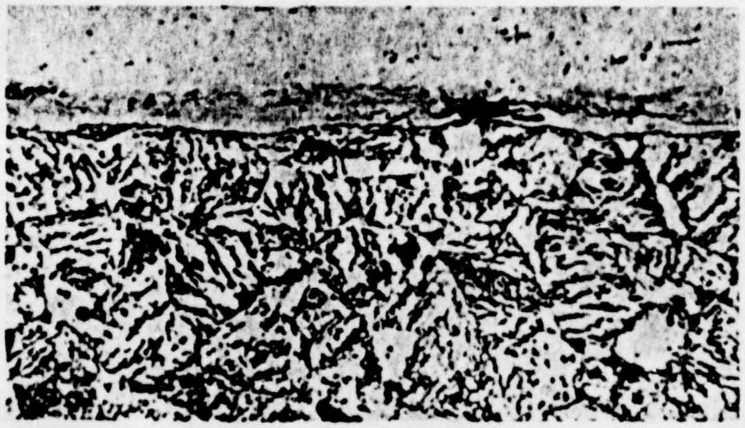
(a) Nylon 11(A).

7A-3, After test

7A-3, Blisters opened.

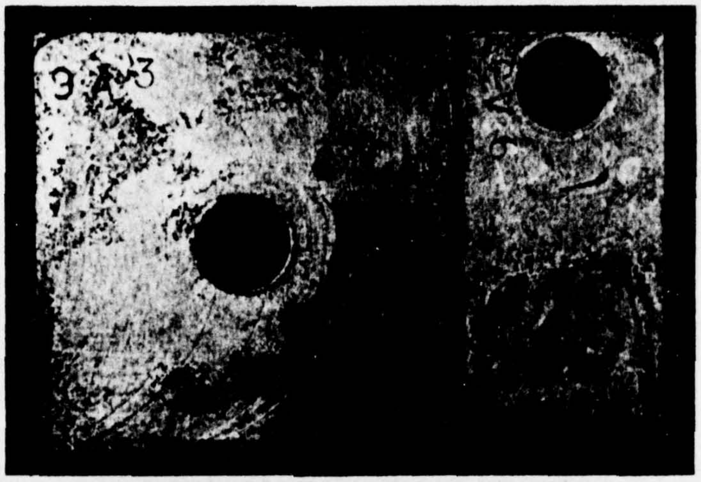
(b) Nylon 11(B).

FIGURE B-4. NYLON 11 CORROSION COUPONS. Series 3, 276 days. MIL-H-5559 Hydraulic Fluid.

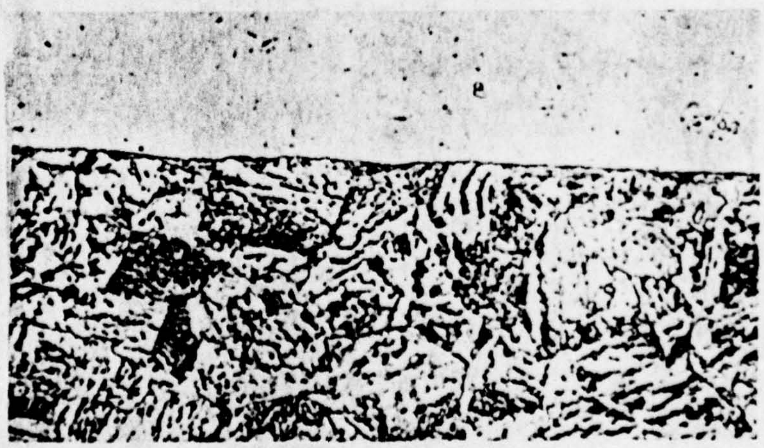


Section through direct exposure coupon. Specimen nickel plated prior to sectioning. 1000X.

FIGURE B-5. SELECTRON Ni-W CORROSION COUPON AFTER CLEANING. Series 3, 253 days. MIL-H-5559 Hydraulic Fluid.



(a) Specimen 9B-3.



(b) Section through direct exposure coupon at location of complete loss of coating. Specimen nickel plated prior to sectioning. 1000X.

FIGURE B-6. SELECTRON Ni-Co CORROSION COUPONS AFTER CLEANING. Series 3, 253 days. MIL-H-5559 Hydraulic Fluid.

APPENDIX C

CORROSION TEST DATA - PHASE I

MIL-H-22072 Hydraulic Fluid (Catapult Accumulator)

CORROSION TEST DATA SHEET

Coating: Hytrel

Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	2B-1	30	+0.0737	N/A
	2B-2	95	N/A	N/A
	2B-3	95	N/A	N/A
Coated Crevice Coupon	2B-1	30	+0.0455	N/A
	2B-2	95	N/A	N/A
	2B-3	95	N/A	N/A
Bronze Crevice Coupon	2B-1	30	+0.0147	N/A
	2B-2	95	N/A	N/A
	2B-3	95	N/A	N/A

NOTES:

1. Small blisters in direct exposure and crevice coupon in Series 1 tests. Deleted from Phase II tests because of blistering.

2. All Series 2 and Series 3 coupons failed due to severe peeling after 95 day exposure period, see Figure C-1(a). Test terminated after 95 days.

CORROSION TEST DATA SHEET

Coating: LW-11B

Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	3B-1	36	-0.1409	N/A
	3B-2	181	-0.5797	N/A
	3B-3	269	-1.1544	-4.1859
Coated Crevice Coupon	3B-1	36	-0.0690	N/A
	3B-2	181	+0.4841	N/A
	3B-3	269	-0.6099	-4.4119
Bronze Crevice Coupon	3B-1	36	-0.0393	N/A
	3B-2	181	-0.1117	N/A
	3B-3	269	-0.2018	-0.1425

NOTES:

1. Appearance of Series 1 test coupons suggested general corrosive attack. Deleted from Phase II test program.

2. All Series 2 and Series 3 coupons showed evidence of coating attack and rusting of substrate.

3. Definite loss of plating and corrosive attack of substrate apparent in Series 3 tests, see Figure C-1(b).

CORROSION TEST DATA SHEET

Coating: Nylon 11(B) Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	7B-1	26	+0.2540	N/A
	7B-2	186	+0.1098	N/A
	7B-3	234	+0.1225	N/A
Coated Crevice Coupon	7B-1	26	+0.0760	N/A
	7B-2	186	+0.0576	N/A
	7B-3	234	+0.0873	N/A
Bronze Crevice Coupon	7B-1	26	-0.0231	N/A
	7B-2	186	-0.1389	N/A
	7B-3	234	-0.2369	-0.2348

NOTES:

1. No visual evidence of coating damage in Series 1 and Series 2 tests except for one blister on Series 2 crevice corrosion specimen.

2. Major blisters in all Series 3 specimens, see Figure A-4(b).

3. Blisters contained fluid when opened.

CORROSION TEST DATA SHEET

Coating: Diamonized

Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	10B-1	26	-0.0010	N/A
	10B-2	186	-0.0052	N/A
	10B-3	273	-0.0249	-0.3177
Coated Crevice Coupon	10B-1	26	-0.0005	N/A
	10B-2	186	-0.0028	N/A
	10B-3	273	+0.0224	-0.1117
Bronze Crevice Coupon	10B-1	26	-0.0180	N/A
	10B-2	186	-0.1301	N/A
	10B-3	273	-0.1718	-0.2268

NOTES:

1. Slight roughening and localized areas of small pits in Series 1 and Series 2 tests.

2. Severe attack by pitting of coating and corrosive attack of substrate at pits, see Figure C-1(d).

CORROSION TEST DATA SHEET

Coating: Nye-Kote   Fluid: MIL-H-22072

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	11B-1	30	+0.0009	N/A
	11B-2	105	N/A	N/A
	11B-3	105	N/A	-0.0569
Coated Crevice Coupon	11B-1	30	+0.0009	N/A
	11B-2	105	N/A	N/A
	11B-3	105	N/A	-0.0184
Bronze Crevice Coupon	11B-1	30	-0.0048	N/A
	11B-2	105	N/A	N/A
	11B-3	105	N/A	-0.0593

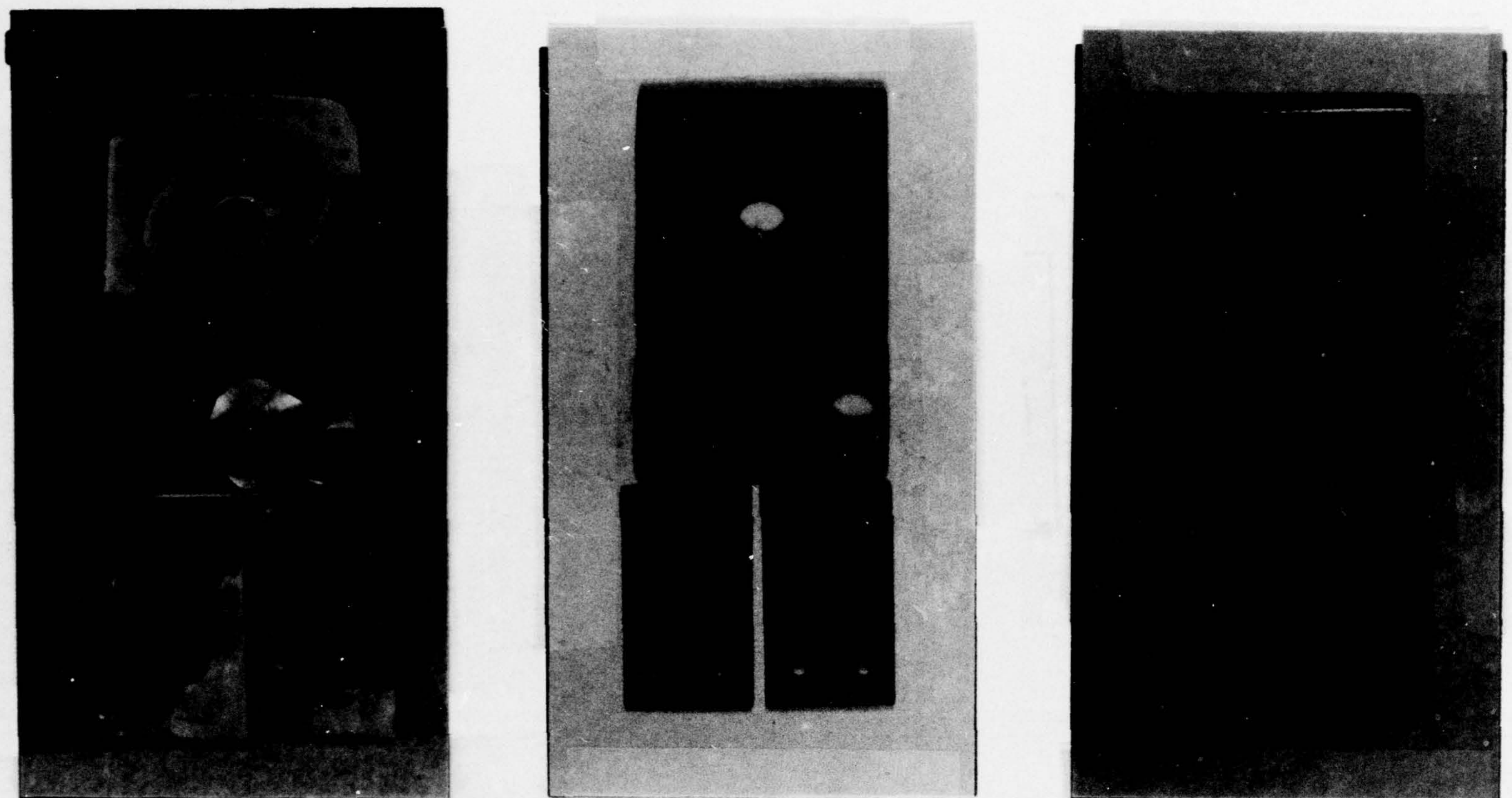
NOTES:

1. No significant change in Series 1 tests.

2. Darker color and evidence of mild coating attack in Series 2 tests.

3. Localized areas of more severe attack in Series 3 tests. Generally darker appearance, see Figure C-1(e).

4. Series 2 and Series 3 terminated after 105 days when Nye-Kote specimens failed in MIL-H-5559 fluid. (See Appendix D, pg. D-6).

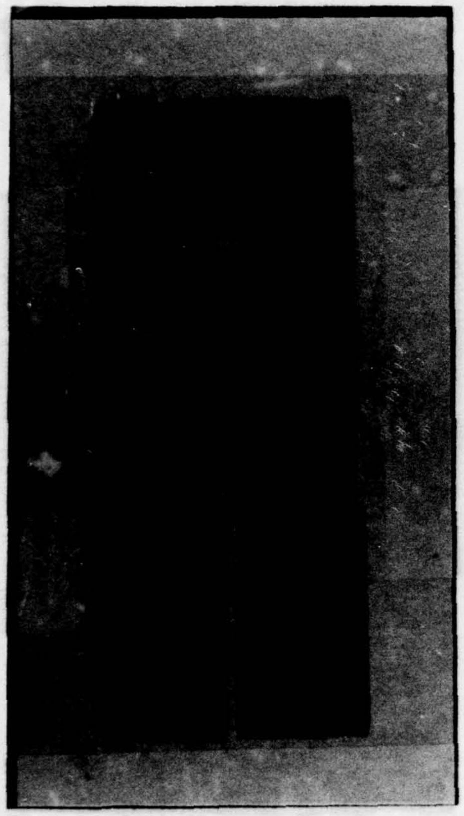


(a) Hytrel.
(2B-3, 95 days).

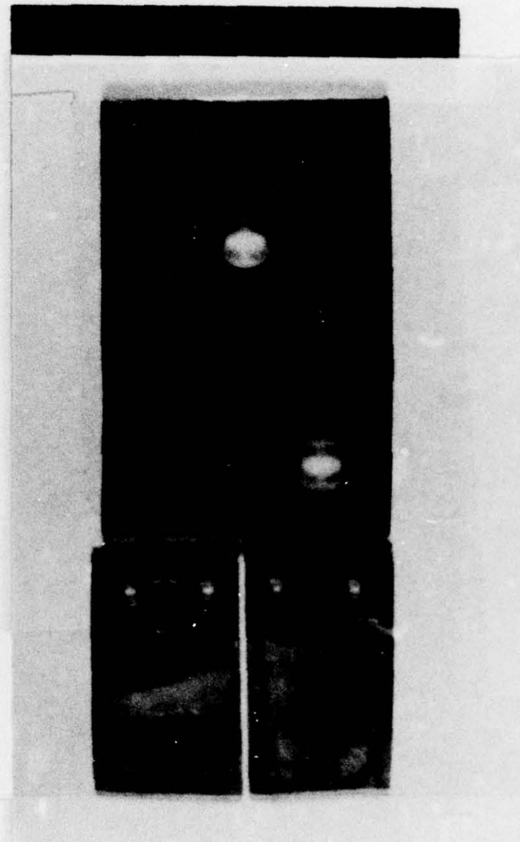
(b) LW-11B.
(3B-3, 269 days).

(c) Nylon 11 (A)
(7B-3, 234 days).

FIGURE C-1. SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS.
MIL-H-22072 Hydraulic Fluid (Catapult Accumulator).



(d) Diamondised.
(10B-3, 273 days).



(e) Nye-Kote.
(11B-3, 105 days).

FIGURE C-1 (cont'd). SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS.
MIL-H-22072 Hydraulic Fluid (Catapult Accumulator).

APPENDIX D

CORROSION TEST DATA - PHASE I

MIL-H-5559 Hydraulic Fluid (Arresting Gear)

CORROSION TEST DATA SHEET

Coating: Hytrel

Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	2A-1	30	+0.0805	N/A
	2A-2	95	N/A	N/A
	2A-3	95	N/A	N/A
Coated Crevice Coupon	2A-1	30	+0.0510	N/A
	2A-2	95	N/A	N/A
	2A-3	95	N/A	N/A
Crevice Coupon	2A-1	30	+0.0083	N/A
	2A-2	95	N/A	N/A
	2A-3	95	N/A	N/A

NOTES:

1. No evidence of coating damage in Series 1 tests.

2. Coating on all Series 2 and Series 3 test coupons failed by severe peeling after 95 day exposure period, see Figure D-1(a). Test terminated.

CORROSION TEST DATA SHEET

Coating: LW-11B

Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	3A-1	36	-2.0090	N/A
	3A-2	181	-6.6489	N/A
	3A-3	269	*	-3.8539
Coated Crevice Coupon	3A-1	36	-0.6478	N/A
	3A-2	181	-2.4580	N/A
	3A-3	269	-0.7631	-0.9295
Aluminum Crevice Coupon	3A-1	36	+0.0030	N/A
	3A-2	181	+0.0055	N/A
	3A-3	269	+0.0268	-0.0049

* Weight change not obtained.

NOTES:

1. Dull dark appearance after Series 1 tests. Coating powdery and easily scraped off indicating general corrosive attack. Deleted from Phase II test program on basis of Series 1 tests.

2. Coating severely attacked in Series 2 and Series 3 tests. Dark, powdery and easily scraped off.

CORROSION TEST DATA SHEET

Coating: Nylon 11 (B) Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	7A-1	29	+0.1008	N/A
	7A-2	189	+0.1341	N/A
	7A-3	236	+0.2219	N/A
Coated Crevice Coupon	7A-1	29	+0.0755	N/A
	7A-2	189	+0.0777	N/A
	7A-3	236	+0.0810	N/A
Aluminum Crevice Coupon	7A-1	29	+0.0045	N/A
	7A-2	189	+0.0116	N/A
	7A-3	236	+0.0094	-0.0029

NOTES:

1. No evidence of coating damage in Series 1 tests.
2. Major blisters developed on all coupons in Series 2 and Series 3 tests, see Figure D-1(c) and Figure B-4(b).
3. Blisters contained fluid when opened.

CORROSION TEST DATA SHEET

Coating: Diamonised

Fluid: MIL-H-5559

Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	10A-1	34	-0.1294	N/A
	10A-2	194	-0.8618	N/A
	10A-3	281	-0.0097	-0.1633
Coated Crevice Coupon	10A-1	34	-0.3900	N/A
	10A-2	194	-0.4076	N/A
	10A-3	281	-0.4016	-0.4972
Aluminum Crevice Coupon	10A-1	34	+0.0029	N/A
	10A-2	194	+0.0038	N/A
	10A-3	281	+0.0059	-0.0007

NOTES:

1. Dull color with visual appearance of general attack in Series 1 tests. Coating deleted from Phase II test programs.

2. Definite visual evidence of general corrosive attack of coating in Series 2 and Series 3 tests, before and after cleaning, see Figure D-1(d).

CORROSION TEST DATA SHEET

Coating: Nye-Kote

Fluid: MIL-H-5559

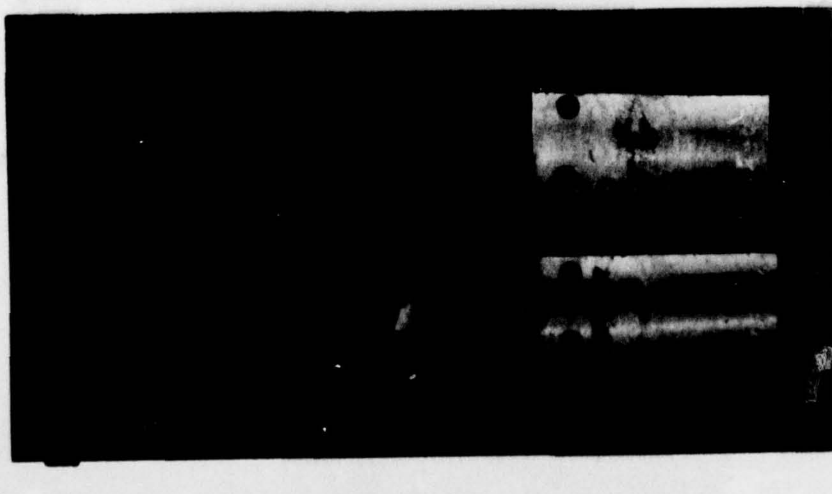
Specimen		Exposure Time days	Weight Change - gm	
Type	No.		Rinsed	Cleaned
Direct Exposure	11A-1	30	-0.5946	N/A
	11A-2	102	*	N/A
	11A-3	102	*	-2.8361
Coated Crevice Coupon	11A-1	30	-0.2872	N/A
	11A-2	133	*	N/A
	11A-3	102	*	-1.3633
Aluminum Crevice Coupon	11A-1	30	+0.0089	N/A
	11A-2	102	*	N/A
	11A-3	102	*	-0.0009

* Weight change not measured.

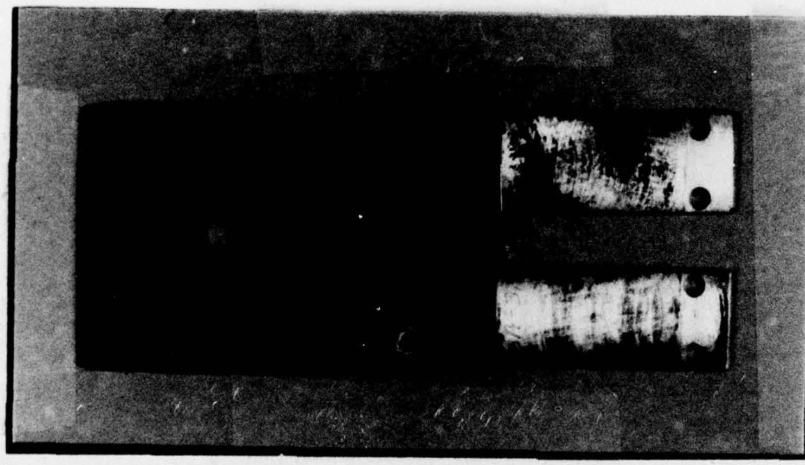
NOTES:

1. Visual evidence of general attack and high weight loss in Series 1 tests. Deleted from Phase II test program.

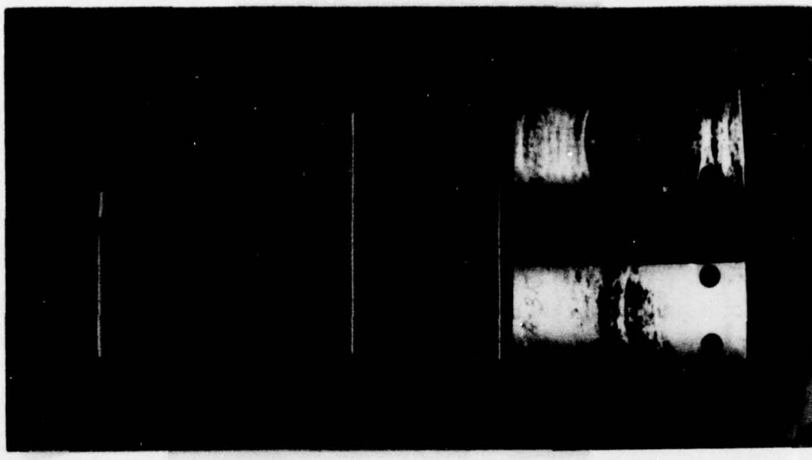
2. Definite visual evidence of coating attack and high weight loss in Series 2 and Series 3 tests.



(a) Hytrel.
(2A-3, 95 days).



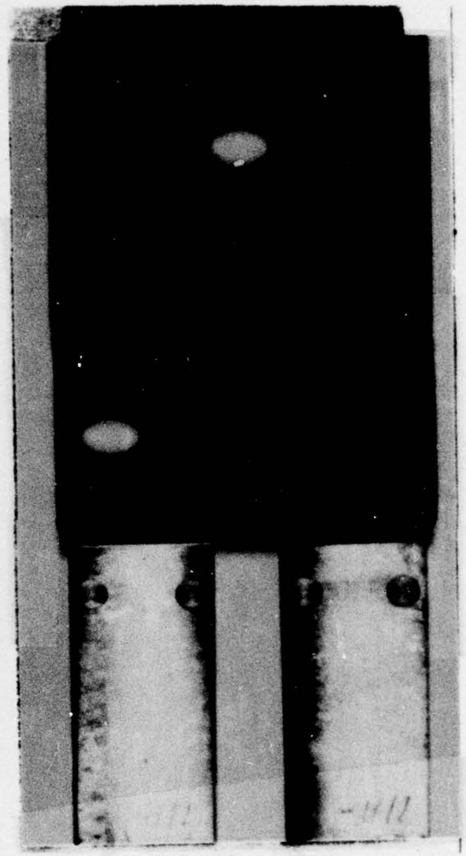
(b) LW-11B
(3A-3, 269 days).



(c) Nylon 11 (A).
(7A-3, 236 days).

FIGURE D-1. SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS.
MIL-H-5559 Hydraulic Fluid (Arresting Gear).

(d) Diamondized.
(10A-3, 281 days).



(e) Nye-Kote.
(11A-3, 102 days).

FIGURE D-1 (cont'd). SERIES 3 ALTERNATE IMMERSION CORROSION TEST COUPONS. MIL-H-5559 Hydraulic Fluid (Arresting Gear).

Evaluation of Coatings for Air/Fluid Accumulators NAEC-ENG-7884

Ten coatings were evaluated for wear and corrosion protection of AISI 4130 steel under conditions simulating those in catapult and arresting gear accumulators on aircraft carriers. Tribaloy 800 appears to be the best coating for protection of both catapult and arresting gear accumulators. Other satisfactory coatings, in order of decreasing effectiveness, were Nedox and Selectron Ni-Co for the catapult accumulator and Selectron Ni-W and Nedox in the arresting gear accumulator. A Nylon 11 coating failed because of coating blistering in both corrosion and wear tests.

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